Hitomi Experience Report: Investigation of Anomalies Affecting the X-ray Astronomy Satellite "Hitomi" (ASTRO-H)

May 24, 2016

JAXA

All times are given in JST unless stated otherwise.

Agenda

1. Summary
2. Background information on ASTRO-H
3. Anomaly description and ground-based observations
4. Causes of the anomaly
5. Factors contributing to the anomaly
6. Measures and reforms (to be proposed in the next committee meeting)
7. Summary (to be proposed in the next committee meeting)

1. SUMMARY

1. Summary

- After the anomaly in communications with the X-ray Astronomy Satellite “Hitomi” (ASTRO-H), the Japan Aerospace Exploration Agency (JAXA) set up an emergency headquarters to perform investigations and consider measures for future operations.
- For the cause analysis, experts from every branch of JAXA collaborated in the investigations such as analysis of telemetry data sent from the satellite, simulations, examination of the design, and analysis of the ground test data. In addition, the private enterprises that developed the satellite with JAXA also helped with the investigations.
- JAXA have been inspecting the direct causes and extending the investigation to trace back to the design policy and process in order to determine the design of the spacecraft. In Chapter 2 and later, JAXA reports the current status of the investigation.

2. BACKGROUND INFORMATION ON ASTRO-H

2.1 Mission Overview

- ASTRO-H was developed to reveal the structure and evolution of the universe by observing high-energy objects that are visible in the X-ray and gamma-ray bands, objects such as black holes, supernova remnants (SNRs), and galaxy clusters.

- X-rays and gamma-rays from space cannot penetrate the barrier of Earth's atmosphere. It is therefore necessary to use a satellite outside of Earth's atmosphere.

- ASTRO-H, the successor of "Suzaku", was developed through an international collaboration including Japan and NASA. More than 250 researchers joined in this flagship mission. The four cutting-edge instruments on board Hitomi were expected to enable acquisition of spectra of objects that were 10 to 100 times fainter than those that could be observed by Suzaku.

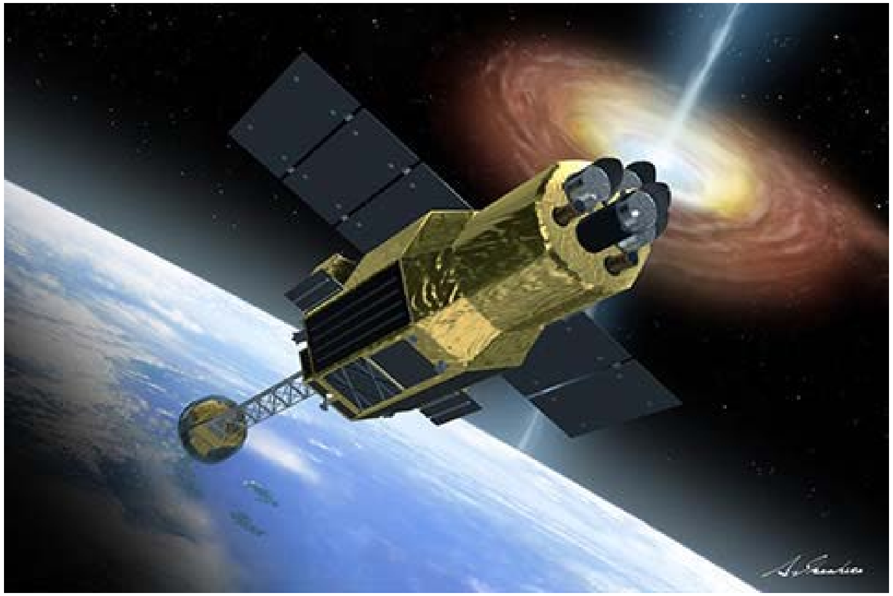
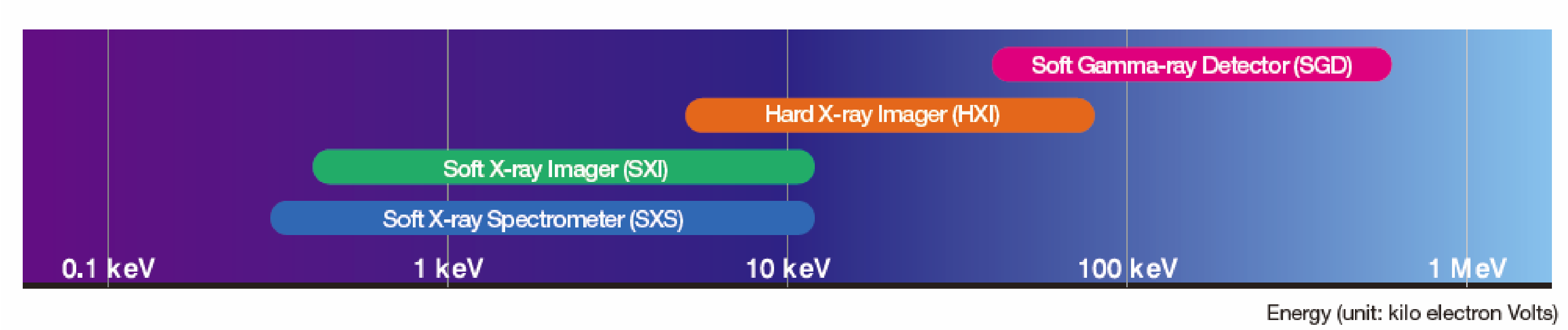


Illustration of ASTRO-H in orbit

2.1 Mission Summary (Characteristics)



Soft X-Ray Spectroscopy

SXT-S (Telescope) | SXS

Ultrahigh-precision spectroscopy by combining the state-of-art SXT-S with a detector cooled to 50 mK.

Soft X-Ray Imaging

SXT-I (Telescope) | SXI

Imaging of a large field of view by combining SXT-I with a CCD detector having a large area and low noise. Images acquired with SXT-I serve as the base for other observations.

Hard X-Ray Imaging

HXT (Telescope) | HXI

High-efficiency detector using a CdTe semiconductor device combined with the cutting-edge HXT enables, for the first time, imaging observations in the hard X-ray region, as well as a drastic improvement of sensitivity.

Soft Gamma-Ray Imaging

SGD

The ultralow-noise gamma-ray detector using the Japanese concept of a “small-field Si/CdTe multilayered semiconductor Compton camera” improves sensitivity by an order of magnitude and enables gamma-ray polarimetry.

During simultaneously operation, these four observational systems have wavelength coverage spanning up to three order of magnitude, and can make observations with 10-100 times higher sensitivity.

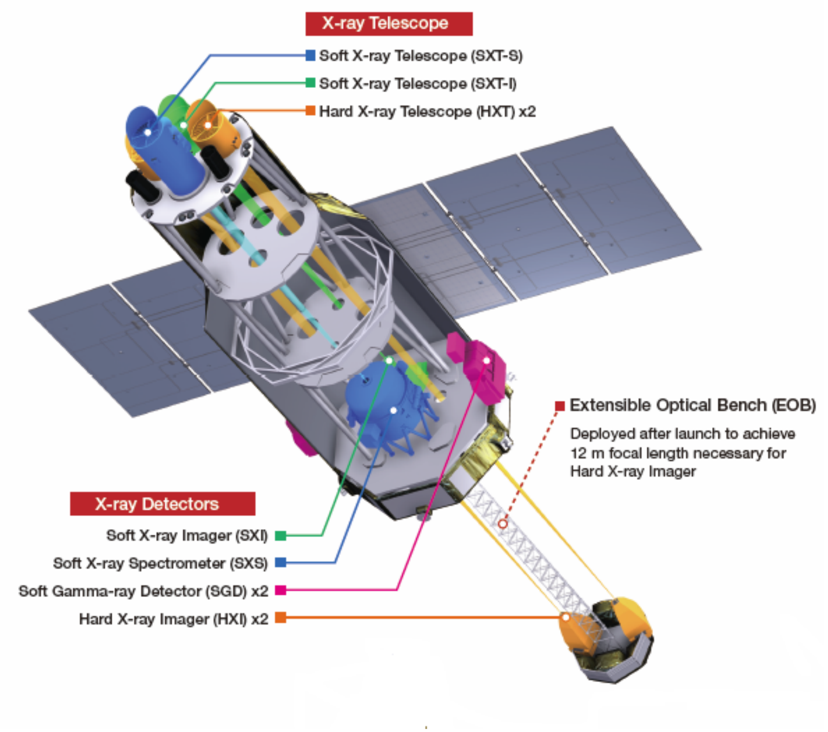
2.2 Requirements and Mission Success Criteria

Aims	Minimum Success	Full Success	Extra Success
Direct observations of the assembly of galaxy clusters	Acquire spectra of the iron emission lines from galaxy clusters by SXS	1) Observing the thermal energy of representative galaxy clusters. Realizing velocity resolution of 300 km/s in the energy range of the iron emission lines (6 KeV). Measuring the kinetic energy of matter constituting galaxy clusters. In the soft X-ray band, measuring non-thermal energy based on spectra acquired with sensitivity 100 times higher than that of Suzaku.	-
Evolution of massive black holes and their role in the formation of galaxies	Acquire images of harbored black holes that are 100,000 times fainter than the Crab Nebula in 100 ks	2) Acquiring spectra of approximately 10 objects that are candidates to harbor black holes with sensitivity 100 times higher than that of Suzaku. Revealing the relation between the black holes and their host galaxies.	Clarify the contribution of the harbored black holes to the cosmic hard X-ray background radiation. Understanding their relation with galaxy evolution.
Understanding of the structure of relativistic space-time near a black hole	-	3) Observing continuum emissions from several active galactic nuclei at a resolution of around 10 keV. At the same time, observing emission and absorption lines with a resolution of 7 eV.	-
Clarification of the process producing cosmic rays by the energy released by gravity, collisions, and explosions	-	4) Acquiring hard X-ray spectra of several young SNRs to measure the hard X-ray radiation and determine the energy distribution of electrons. Spectral energy distribution of massive black holes is a power of 1.7. Observing about 10 massive black holes of 100,000 times fainter than the Crab Nebula and acquiring their spectra up to 600 keV.	Observe the polarimetry of objects in the gamma-ray region. Place constraints on the possible condition of gamma-ray radiations.
Exploration of the roles played by dark matter and dark energy in the structure formation of the universe	-	-	5) After fulfillment of aim 1), additional 100 clusters will be observed to measure the total mass of dark matter at z<1 (around 8 billion years away from us). Determine the correlation between the total mass and number of clusters at each epoch.

2.3 ASTRO-H Overall Picture

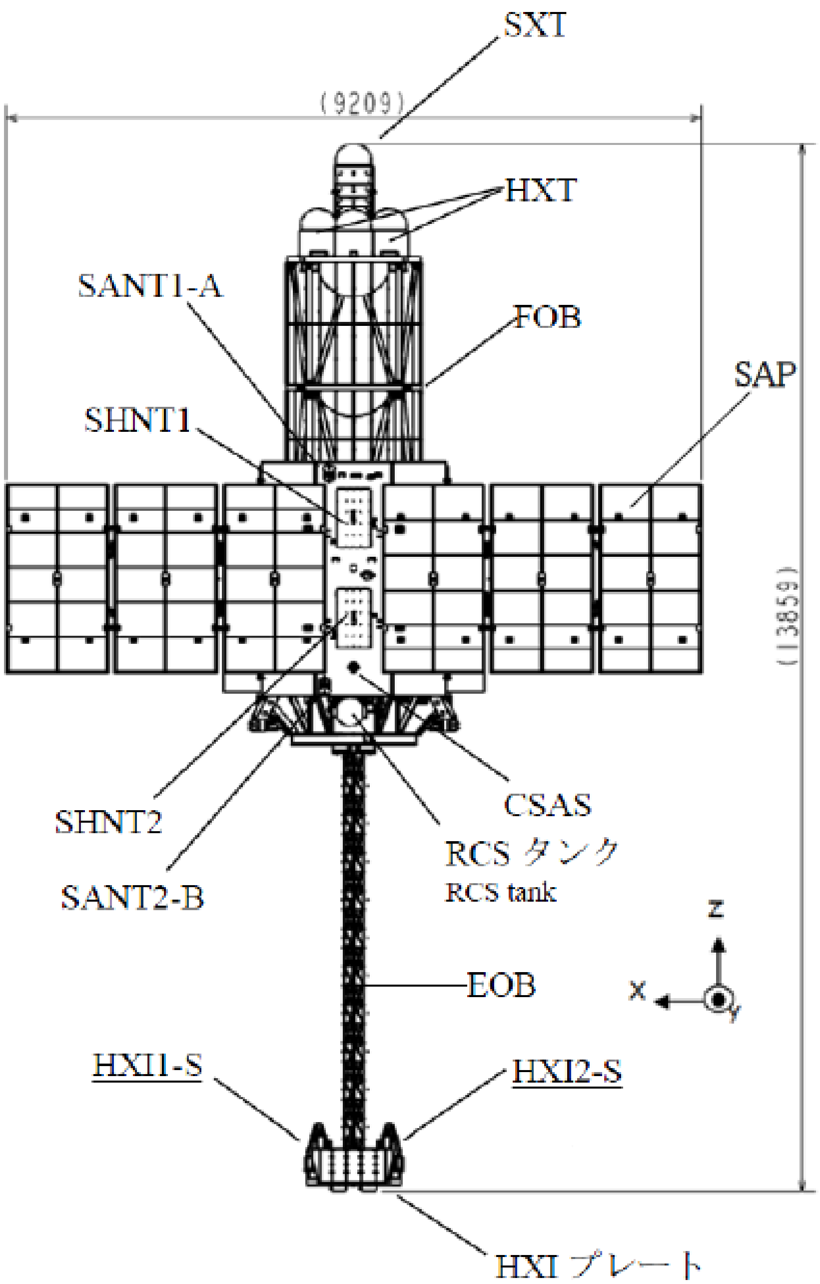
Specifications

Name	X–ray Astronomy Satellite “Hitomi”(ASTRO–H)
Orbit	Type of orbit: Circular Altitude: about 575km Inclination: 31.0 deg Orbital period: about 96 minutes
Lifetime goal	3 years
Total weight	2.7 t
Power consumption	3500W (EOL)
Onboard Instruments	Hard X-ray Telescope(HXT) Soft X-ray Telescope(SXT-S, SXT-I) Hard X-ray Imager(HXT) Soft X-ray Spectrometer(SXS) Soft X-ray Imager(SXI) Soft Gamma-ray Detector(SGD)

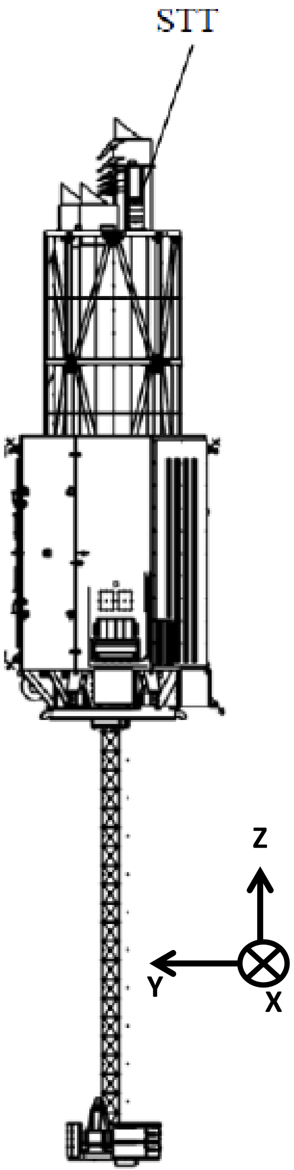


ASTRO–H in orbit

2.3 Exterior view of ASTRO-H satellite

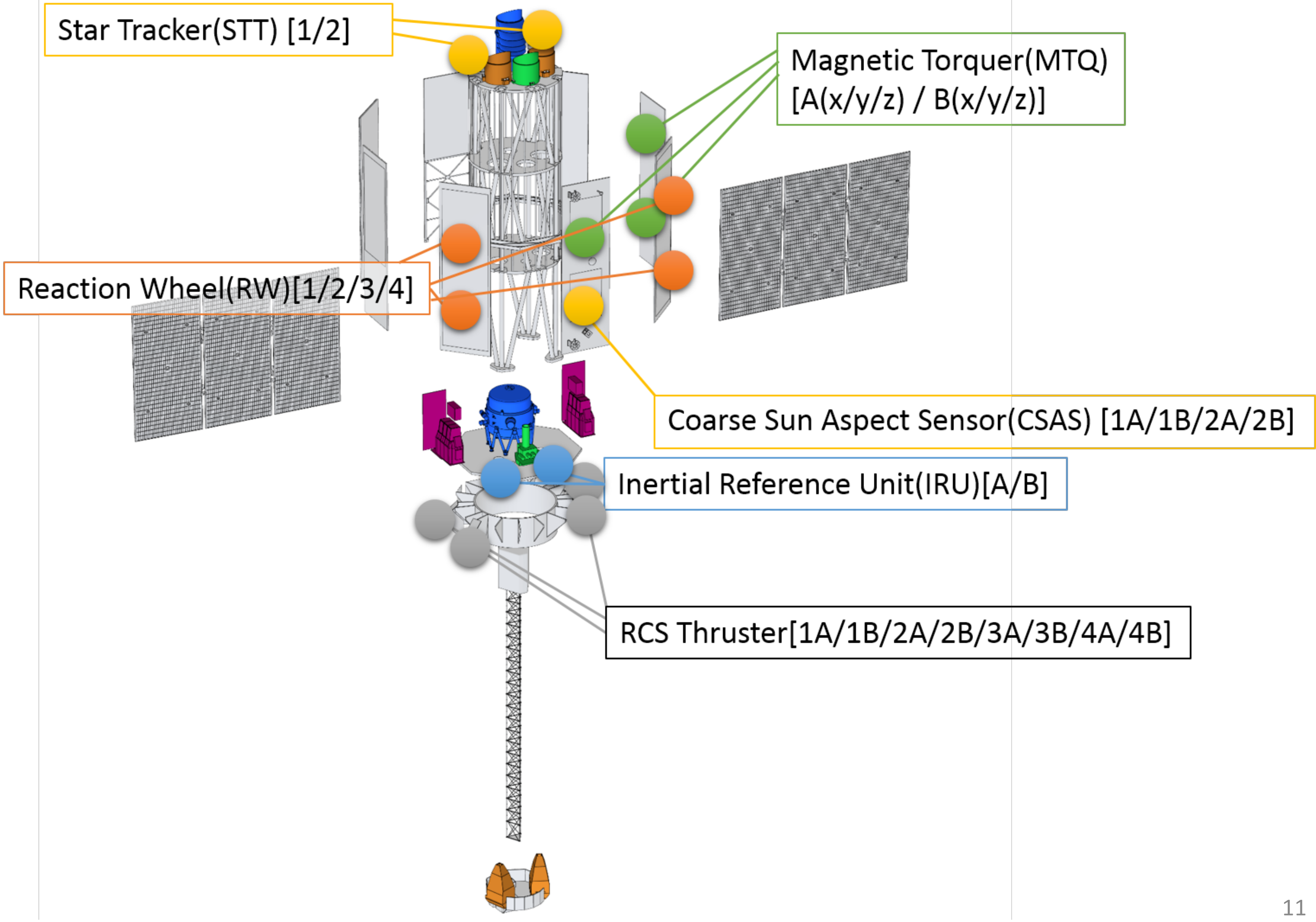


（単位:mm）



abbreviation	Name
SXT	Soft X-ray telescope
HXT	Hard X-ray telescope
SANT	S-band Antenna
FOB	Fixed Optical Bench
SHNT	Shunt Dissipater
SAP	Solar Array Paddle
CSAS	Coarse Sun Aspect Sensor
RCS	Reaction Control System
EOB	Extensible Optical Bench
HXI	Hard X-ray Imager
STT	Star Tracker

2.3 Overview of ASTRO-H ACS



Star Tracker(STT) [1/2]

Magnetic Torquer(MTQ)
[A(x/y/z) / B(x/y/z)]

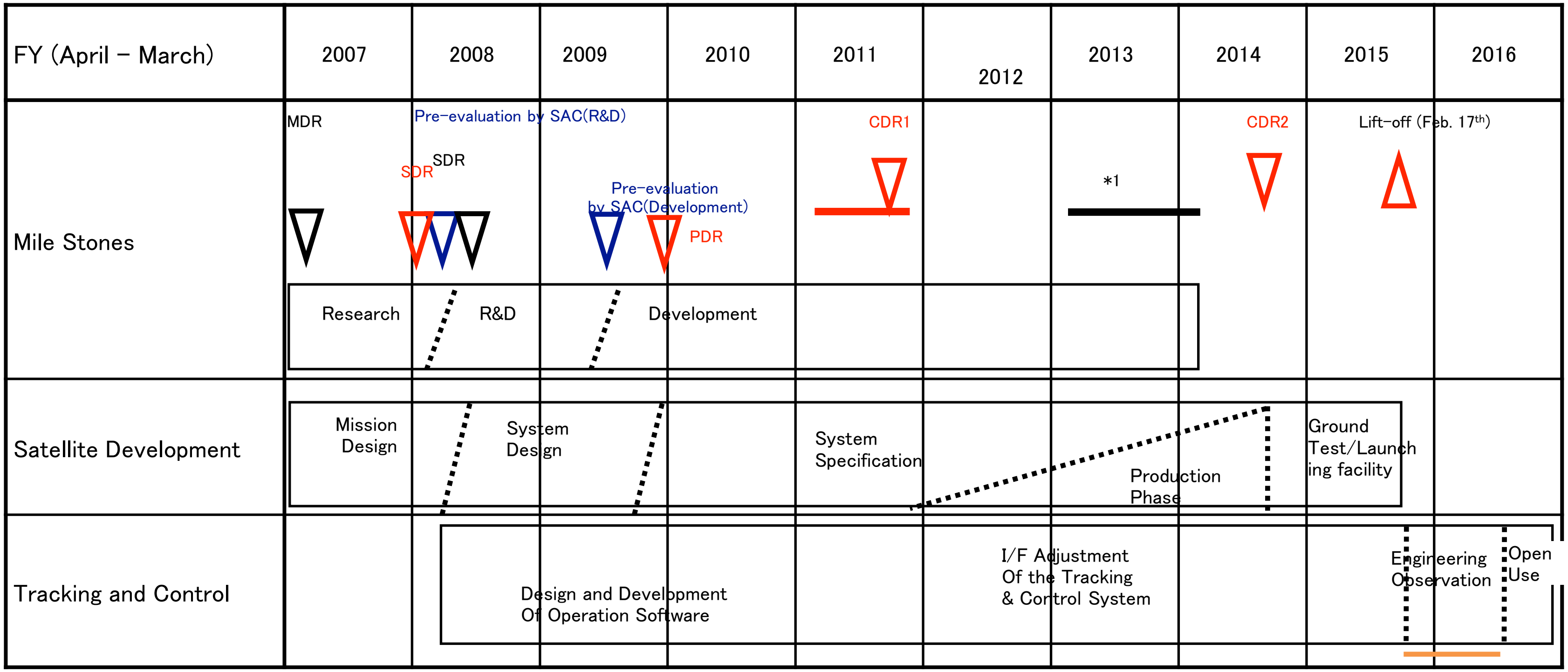
Reaction Wheel(RW)[1/2/3/4]

Coarse Sun Aspect Sensor(CSAS) [1A/1B/2A/2B]

Inertial Reference Unit(IRU)[A/B]

RCS Thruster[1A/1B/2A/2B/3A/3B/4A/4B]

2.4 Development Schedule



FY (April – March)

2007

2008

2009

2010

2011

2012

2013

2014

2015

2016

Mile Stones

MDR

Pre-evaluation by SAC(R&D)

SDR

SDR

Pre-evaluation by SAC(Development)

PDR

CDR1

*1

CDR2

Lift-off (Feb. 17th)

Research

R&D

Development

Satellite Development

Mission Design

System Design

System Specification

Production Phase

Ground Test/Launching facility

Tracking and Control

Design and Development Of Operation Software

I/F Adjustment Of the Tracking & Control System

Engineering Observation

Open Use

On-orbit Operation/Critical Phase/Initial function check phase

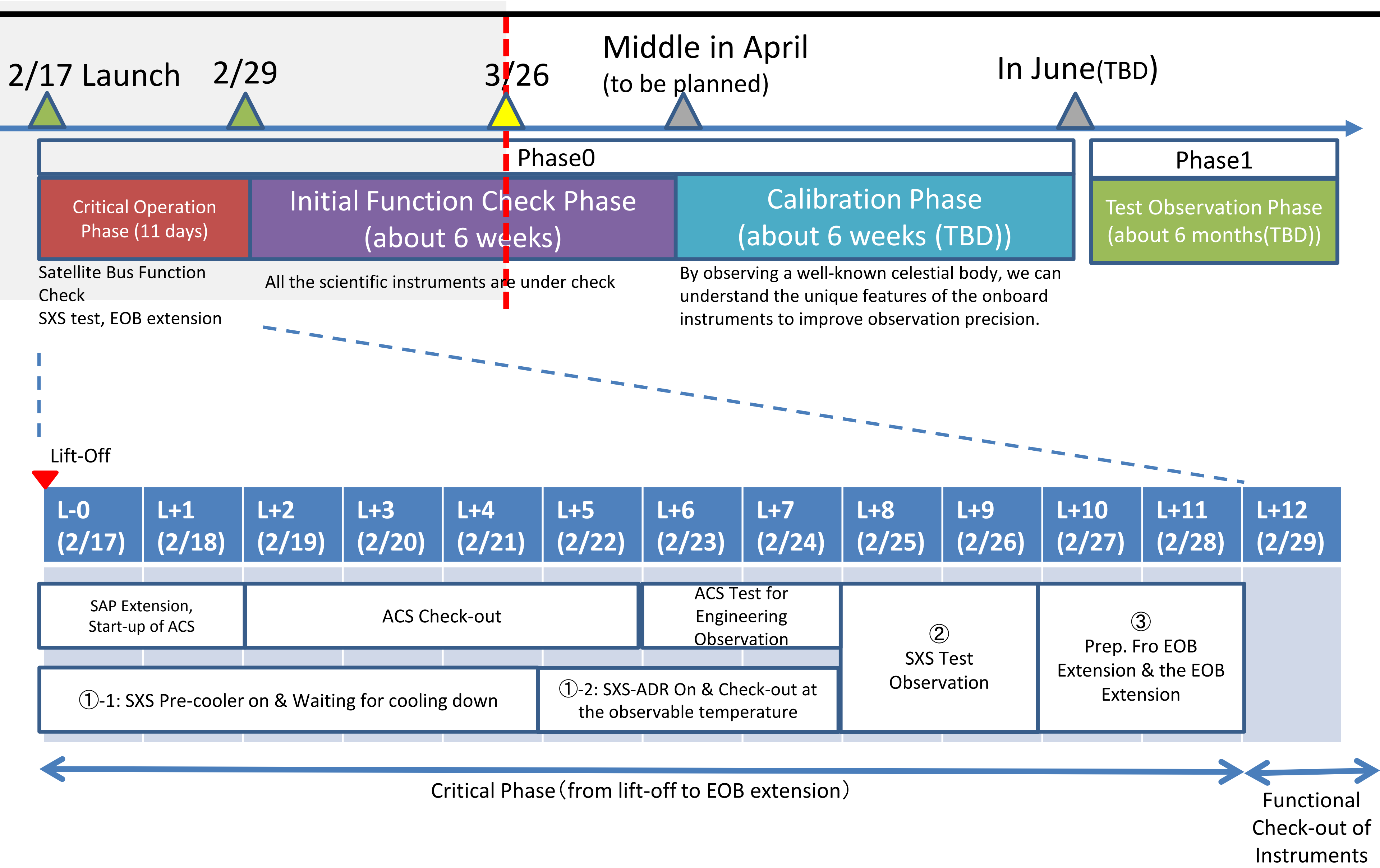
Design/Production(Supply)/Test

*1 Primary Integration Test

Comprehensive Test *

*Groud test of the satellite system

2.4 Schedule (Operation)



2/17 Launch

2/29

3/26

Middle in April
(to be planned)

In June(TBD)

Phase0

Phase1

Critical Operation Phase (11 days)

Initial Function Check Phase (about 6 weeks)

Calibration Phase (about 6 weeks (TBD))

Test Observation Phase (about 6 months(TBD))

Satellite Bus Function Check
SXS test, EOB extension

All the scientific instruments are under check

By observing a well-known celestial body, we can understand the unique features of the onboard instruments to improve observation precision.

Lift-Off

L-0 (2/17)	L+1 (2/18)	L+2 (2/19)	L+3 (2/20)	L+4 (2/21)	L+5 (2/22)	L+6 (2/23)	L+7 (2/24)	L+8 (2/25)	L+9 (2/26)	L+10 (2/27)	L+11 (2/28)	L+12 (2/29)

SAP Extension, Start-up of ACS

ACS Check-out

ACS Test for Engineering Observation

①-1: SXS Pre-cooler on & Waiting for cooling down

①-2: SXS-ADR On & Check-out at the observable temperature

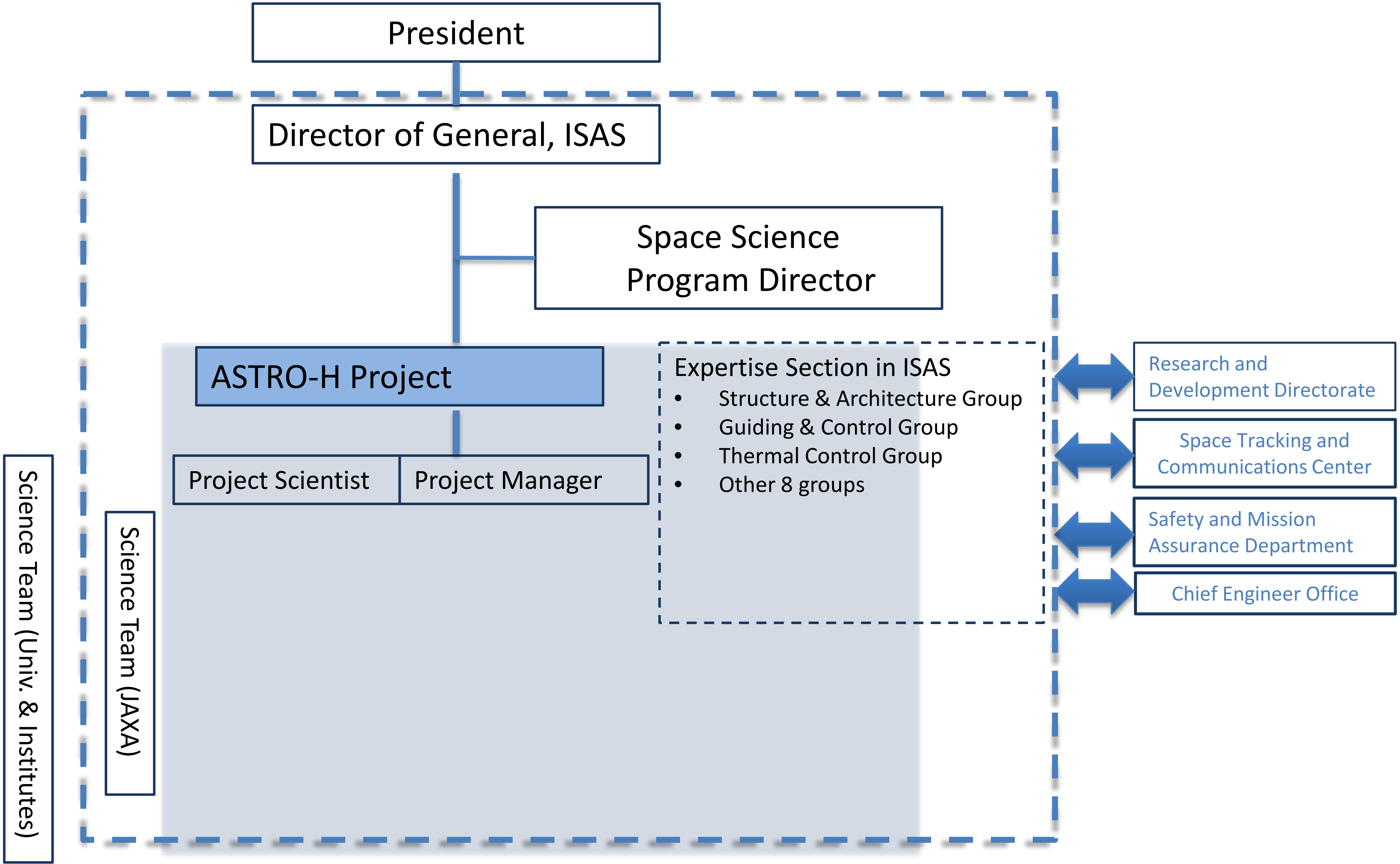
② SXS Test Observation

③ Prep. Fro EOB Extension & the EOB Extension

Critical Phase（from lift-off to EOB extension）

Functional Check-out of Instruments

2.5 Organization Chart (in JAXA)

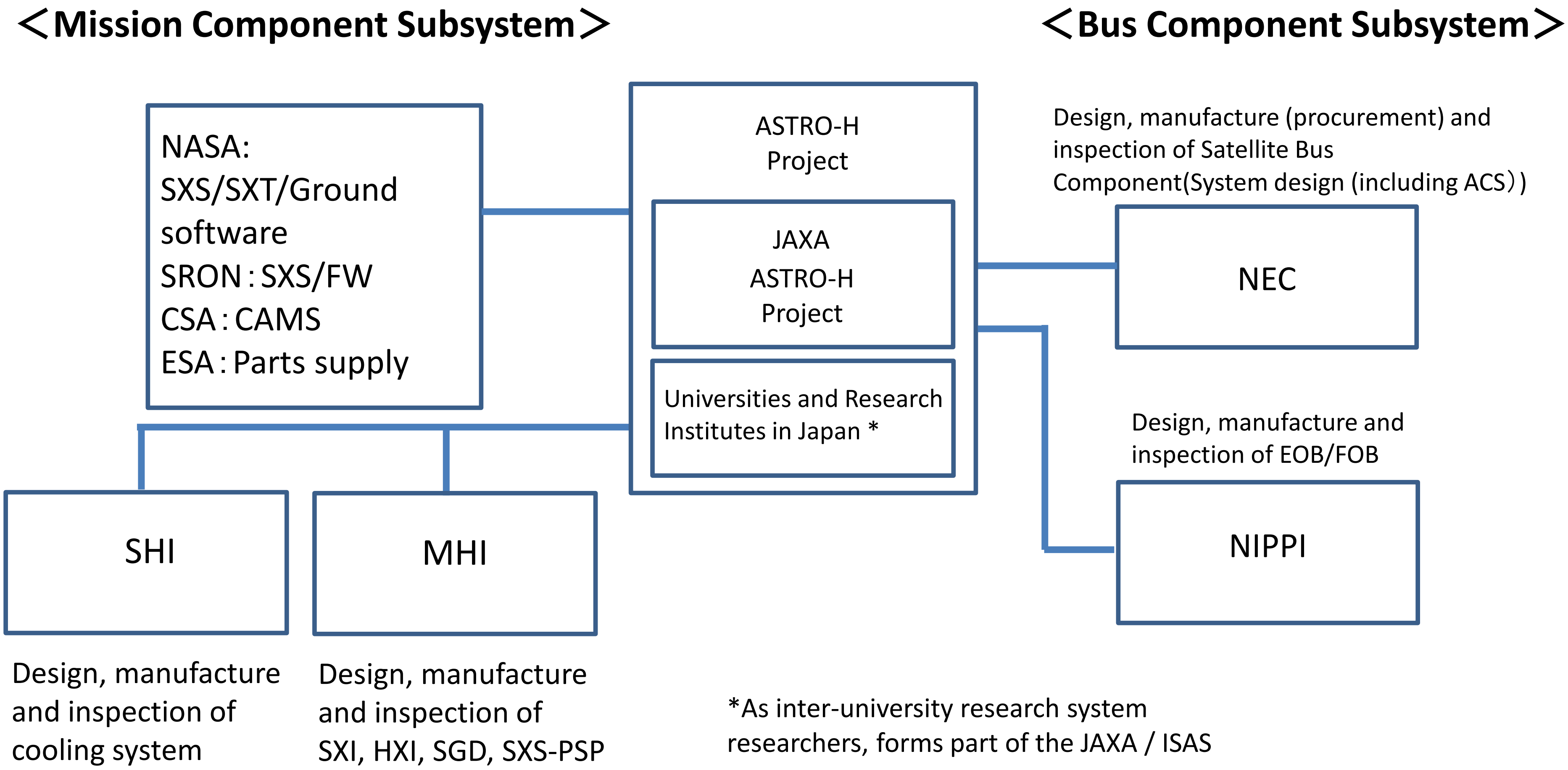


Expertise Section in ISAS

- Structure & Architecture Group
- Guiding & Control Group
- Thermal Control Group
- Other 8 groups

JAXA-institutions/firms relationship diagram(1/3)

Phase of design, manufacture (procurement) and inspection



＜Mission Component Subsystem＞

＜Bus Component Subsystem＞

NASA:
SXS/SXT/Ground software
SRON：SXS/FW
CSA：CAMS
ESA：Parts supply

ASTRO-H Project

JAXA
ASTRO-H
Project

Universities and Research Institutes in Japan *

Design, manufacture (procurement) and inspection of Satellite Bus Component(System design (including ACS）)

NEC

Design, manufacture and inspection of EOB/FOB

NIPPI

SHI

Design, manufacture and inspection of cooling system

MHI

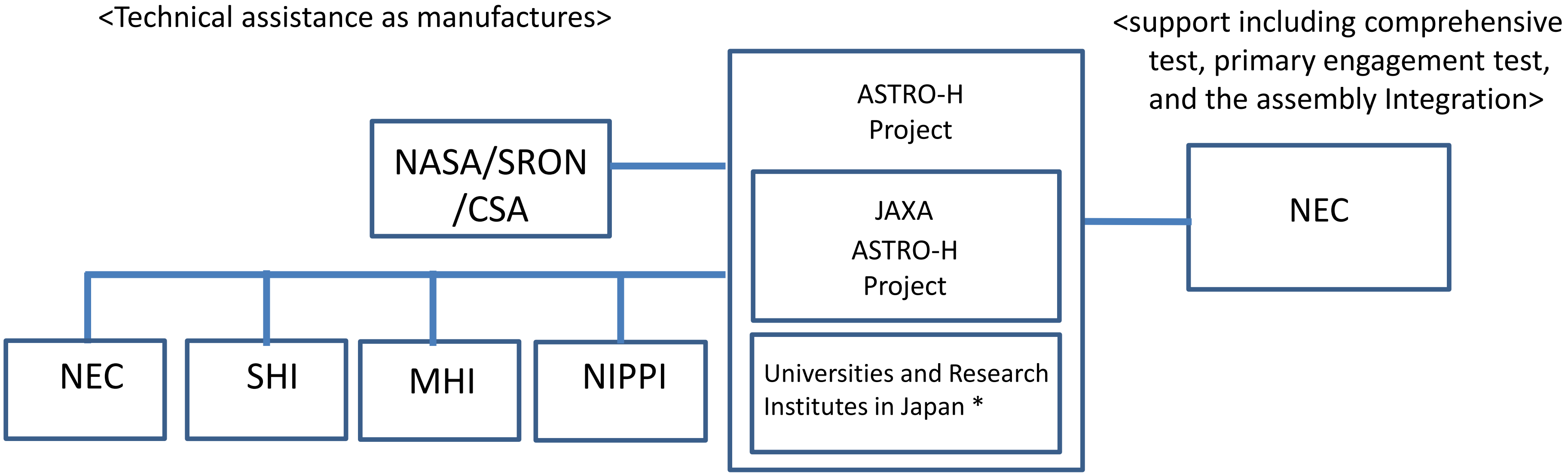
Design, manufacture and inspection of SXI, HXI, SGD, SXS-PSP

*As inter-university research system researchers, forms part of the JAXA / ISAS

JAXA-institutions/firms relationship diagram(2/3)

Phase of satellite system test

(Primary engagement test / satellite comprehensive test)



<Technical assistance as manufactures>

<support including comprehensive test, primary engagement test, and the assembly Integration>

NASA/SRON /CSA

ASTRO-H Project

JAXA ASTRO-H Project

Universities and Research Institutes in Japan *

NEC

NEC

SHI

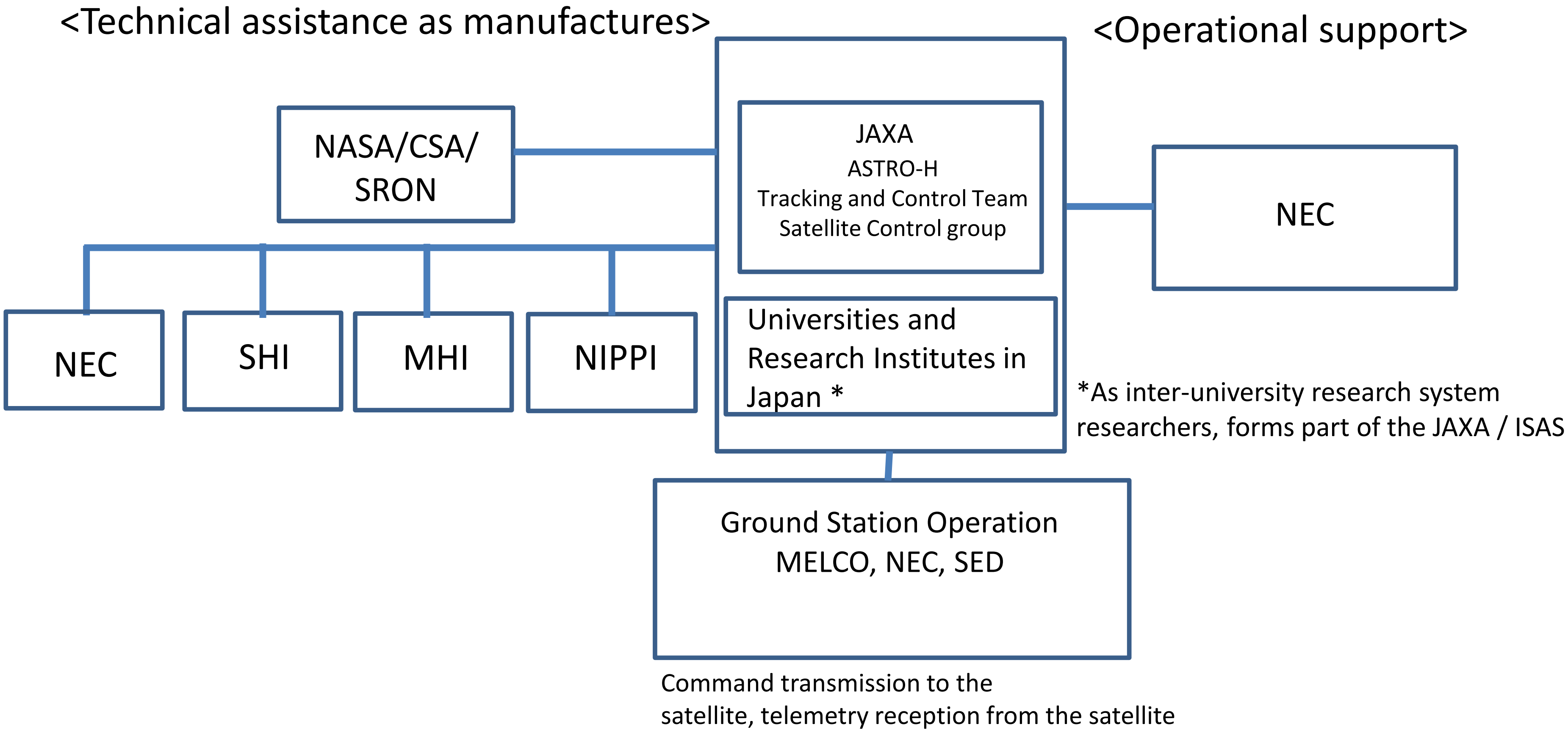
MHI

NIPPI

*As inter-university research system researchers, forms part of the JAXA / ISAS

JAXA-institutions/firms relationship diagram(3/3)

(Flight Operation/Critical Operation Phase /Initial Function Check Phase）



<Technical assistance as manufactures>

<Operational support>

NASA/CSA/
SRON

JAXA
ASTRO-H
Tracking and Control Team
Satellite Control group

NEC

NEC

SHI

MHI

NIPPI

Universities and
Research Institutes in
Japan *

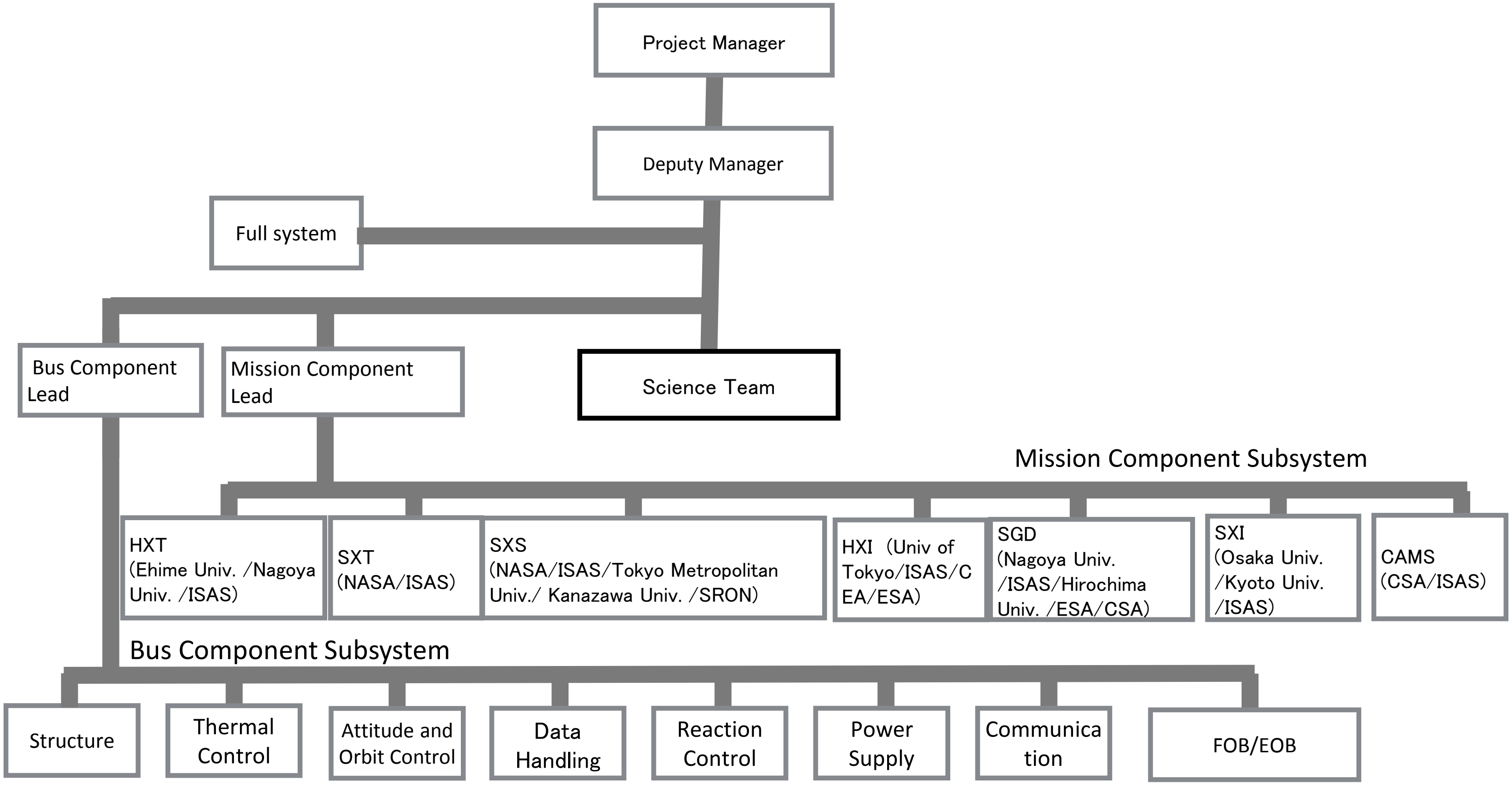
*As inter-university research system researchers, forms part of the JAXA / ISAS

Ground Station Operation
MELCO, NEC, SED

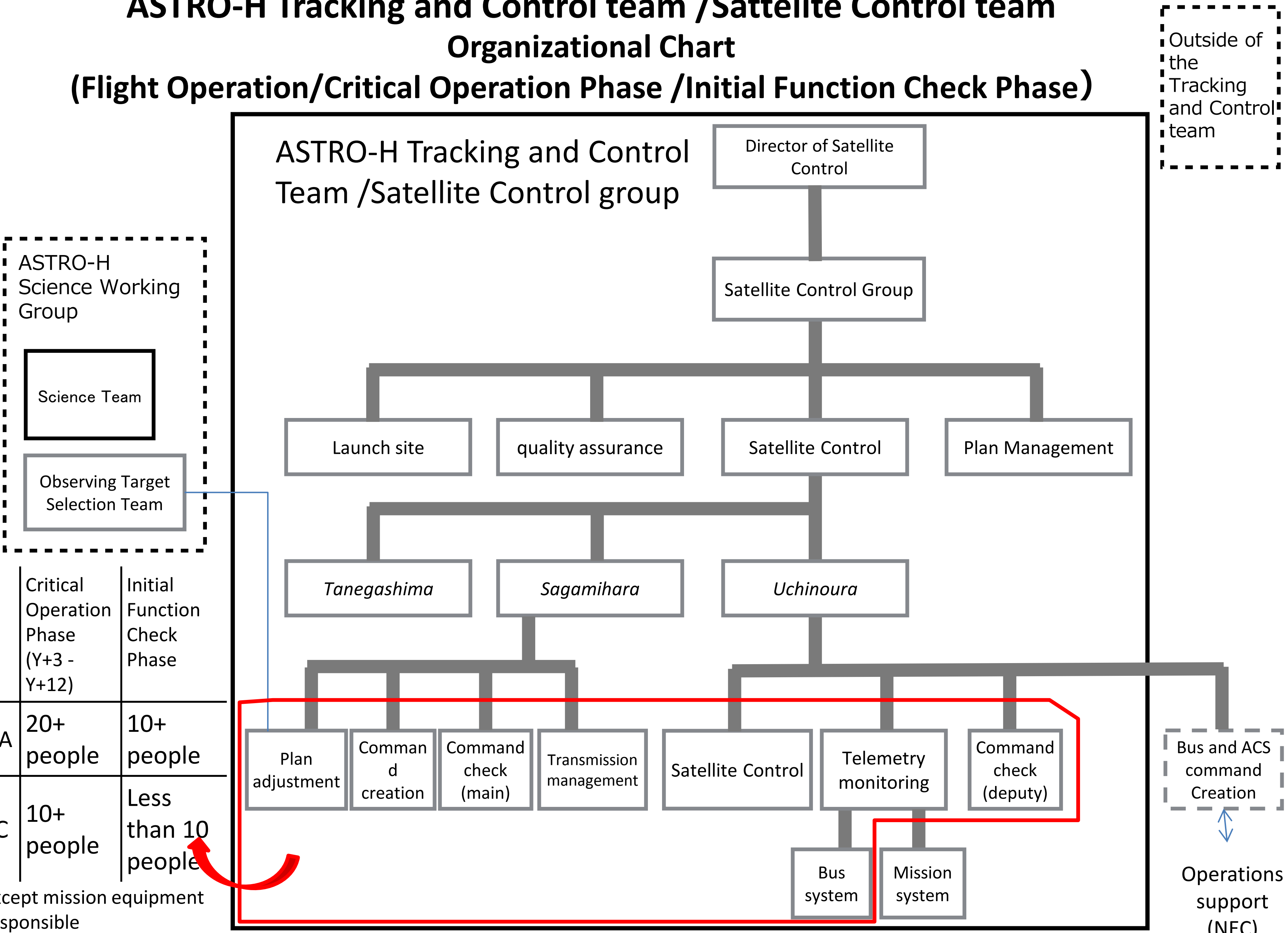
Command transmission to the satellite, telemetry reception from the satellite

ASTRO-H Project Organizational Chart

(In parentheses are Mission Component PI / SubPI institutions ）



ASTRO-H Tracking and Control team /Sattelite Control team
Organizational Chart
(Flight Operation/Critical Operation Phase /Initial Function Check Phase）



Outside of the Tracking and Control team

ASTRO-H Tracking and Control Team /Satellite Control group

Director of Satellite Control

Satellite Control Group

Launch site

quality assurance

Satellite Control

Plan Management

Tanegashima

Sagamihara

Uchinoura

Plan adjustment

Command creation

Command check (main)

Transmission management

Satellite Control

Telemetry monitoring

Command check (deputy)

Bus system

Mission system

Bus and ACS command Creation

Operations support (NEC)

ASTRO-H Science Working Group

Science Team

Observing Target Selection Team

	Critical Operation Phase (Y+3 - Y+12)	Initial Function Check Phase
JAXA	20+ people	10+ people
NEC	10+ people	Less than 10 people

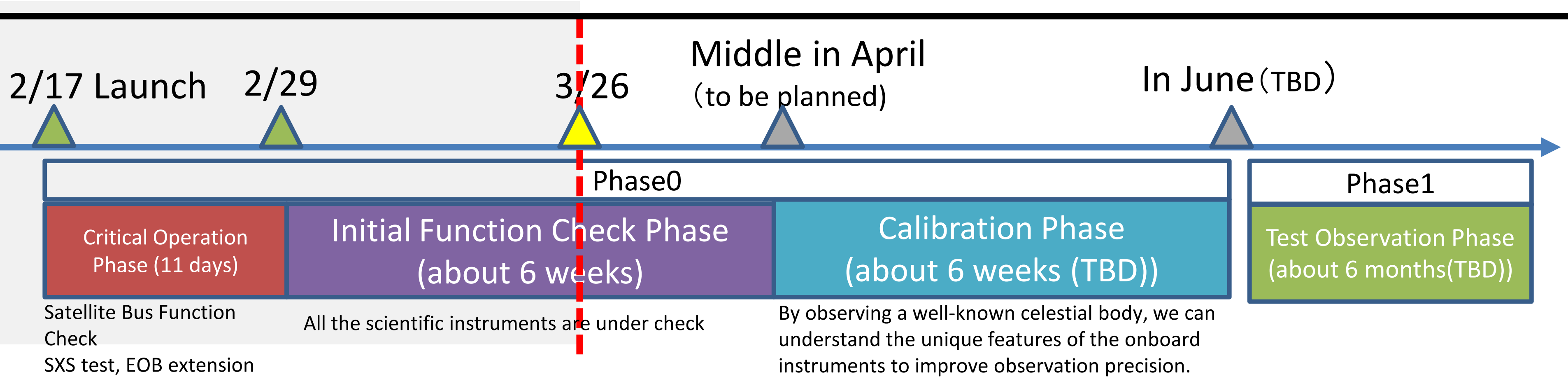
Except mission equipment responsible
(10+ people)

3. ANOMALY DESCRIPTION AND GROUND-BASED OBSERVATIONS

3.1 ASTRO-H Operation

- The health check for all the scientific instruments# has been completed at 26th March, 2016. It was scheduled to proceed with the calibration phase in the middle of April.
- Observation trial for some X-ray bodies was performed on 25th & 26th March, 2016 as preparation for the calibration phase.

\# Soft X-ray Spectrometer（SXS）, Soft X-ray Imager（SXI）, Hard X-ray Imager（HXI）, Soft Gamma-ray Detector（SGD）



2/17 Launch

2/29

3/26

Middle in April
（to be planned)

In June（TBD）

Phase0

Phase1

Critical Operation Phase (11 days)

Initial Function Check Phase (about 6 weeks)

Calibration Phase (about 6 weeks (TBD))

Test Observation Phase (about 6 months(TBD))

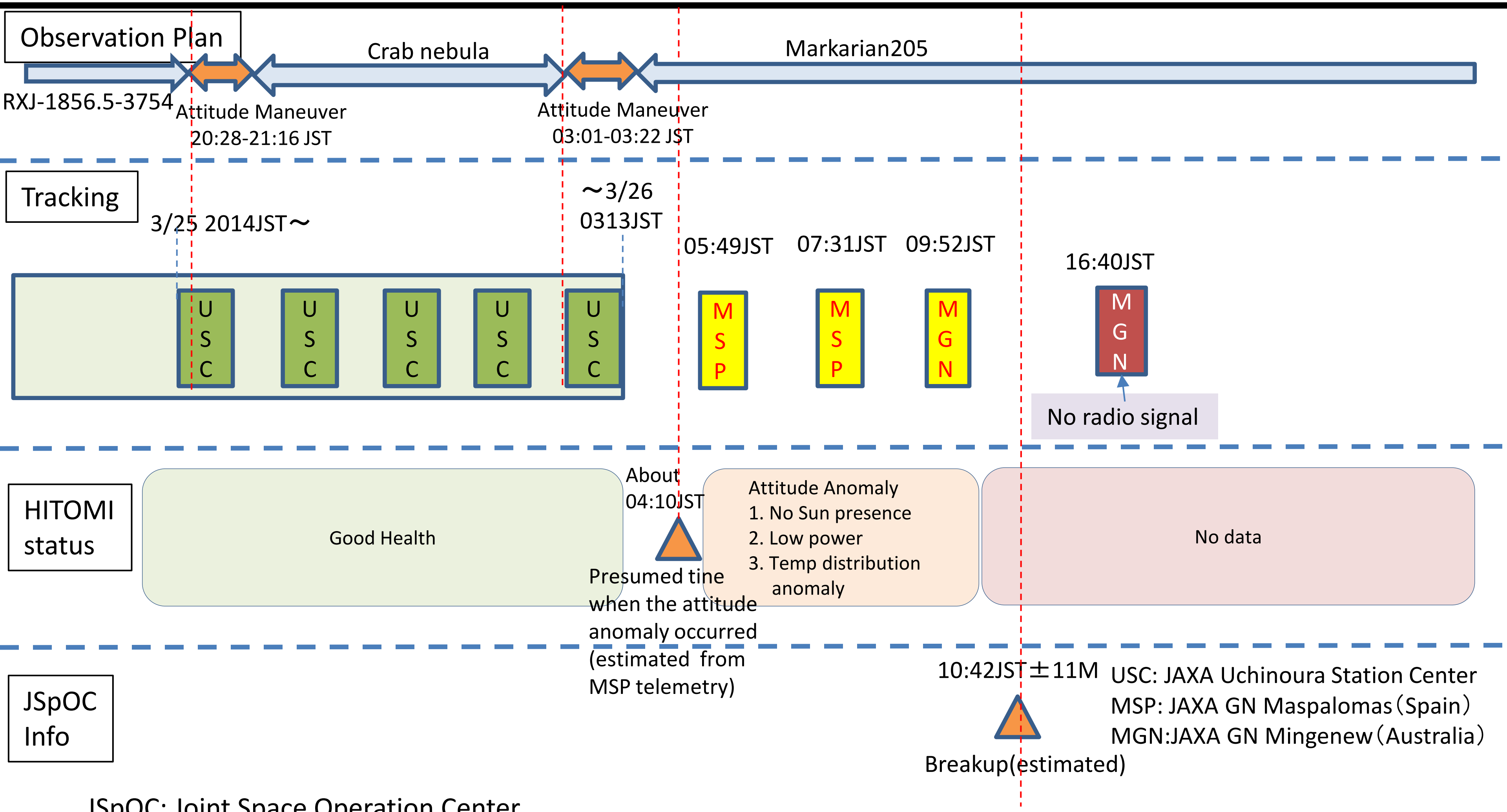
Satellite Bus Function Check
SXS test, EOB extension

All the scientific instruments are under check

By observing a well-known celestial body, we can understand the unique features of the onboard instruments to improve observation precision.

3.2 ASTRO-H Sequence of Event

The chart below shows a time sequence for the observation plan, satellite tracking, satellite condition on each events, and JSpOC information.



Observation Plan

RXJ-1856.5-3754

Attitude Maneuver
20:28-21:16 JST

Crab nebula

Attitude Maneuver
03:01-03:22 JST

Markarian205

Tracking

3/25 2014JST～

～3/26
0313JST

USC USC USC USC USC

05:49JST MSP

07:31JST MSP

09:52JST MGN

16:40JST MGN

No radio signal

HITOMI status

Good Health

About
04:10JST

Presumed tine
when the attitude
anomaly occurred
(estimated from
MSP telemetry)

Attitude Anomaly
1. No Sun presence
2. Low power
3. Temp distribution
anomaly

No data

JSpOC Info

10:42JST±11M

Breakup(estimated)

USC: JAXA Uchinoura Station Center
MSP: JAXA GN Maspalomas（Spain）
MGN:JAXA GN Mingenew（Australia）

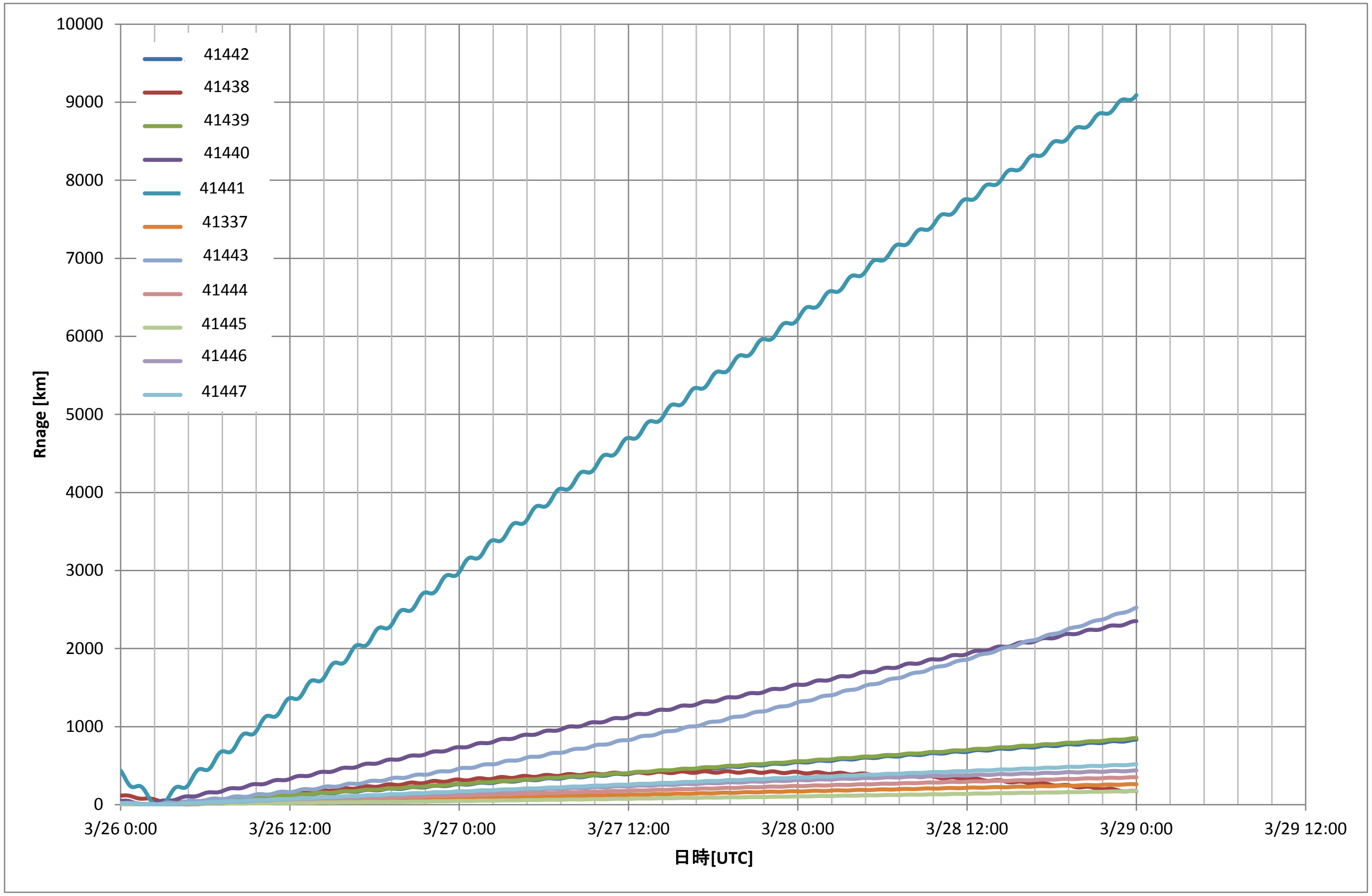
JSpOC: Joint Space Operation Center

3.3 Summary of ASTRO-H Condition based on the last 4 operation HK data

Time (JST)	Station	Attitude	Power	Communication	Data Handling	Temperature Distribution
3/26 03:02 -03:13	USC	Normal	Normal	Normal	Normal	Normal
3/26 05:49 -06:02	MSP	anomaly	Lower power	Normal	Normal	Some parts higher, other parts lower than expected
3/26 07:31 -07:44	MSP	anomaly	Night time	Normal	Normal	Some parts higher, other parts lower than expected
3/26 09:52 -10:04	MGN	anomaly	Lower power（during day time）	Normal	Normal	Some parts higher, other parts lower than expected

3.4 Observation results by ground telescope [1/3]

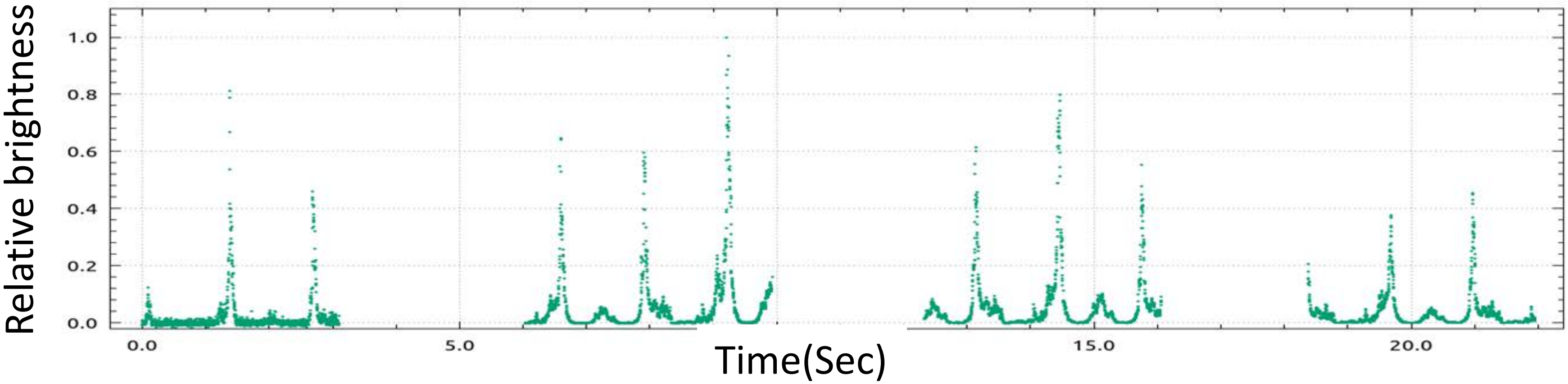
- JSpOC released the trajectory of the 11 objects on April 1. The largest piece should be identified as 41337. In this regards.
- By backtracking the trajectory of 11 objects, it is confirmed that they were on almost the same trajectory as ASTRO-H at 10:37 on 26 March. That shows that those objects are from ASTRO-H satellite.



* JSpOC：Joint SpaceOperations Center

3.4 Observation results by ground telescope [2/3]

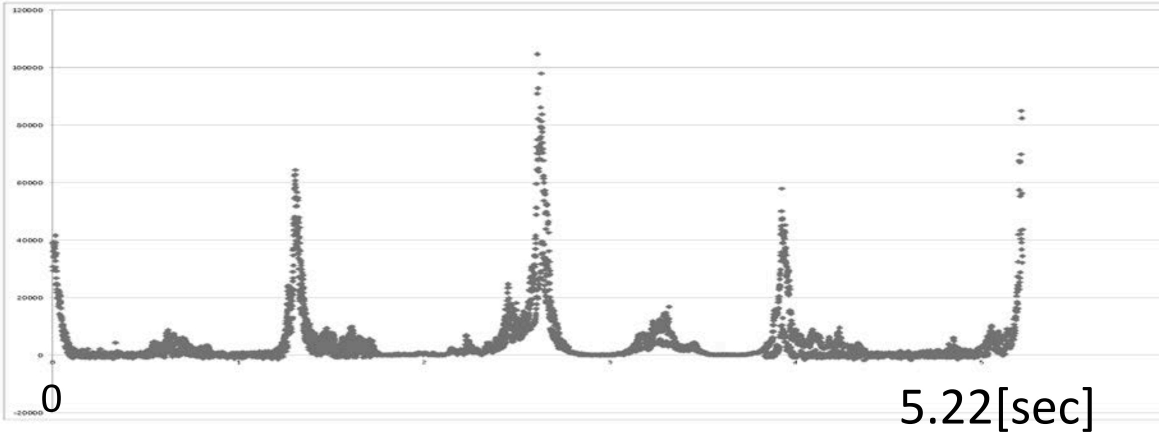
Light Curves observed by KISO Observatory



The number of seconds elapsed from 3/31 11:24:11.3

Upper Panel: Light curves observed by the proto-type of the Kiso wide field CMOS camera.

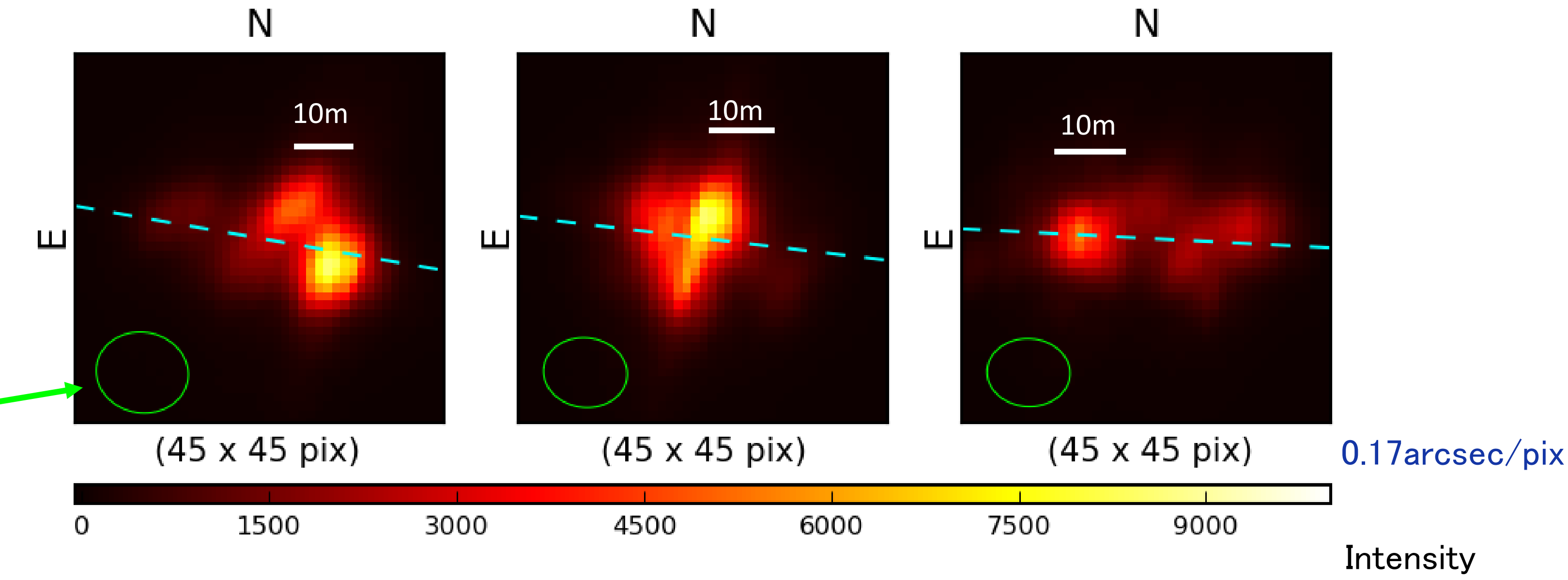
Right Panel: Result of the 5.22 sec period convolution



Original chart is provided by University of Tokyo

3.4 Observation results by ground telescope [3/3]

Observation images by Subaru Telescope



The image of light source may spread in this size.

HSCA06544512 4/2 15:38:13

HSCA06544712 4/2 15:38:49

HSCA06544912 4/2 15:39:35

Original images are provided by National Astronomical Observatory of Japan

Although the resolution is not clear enough due to the low elevation of the target and the tracking error, the size of the bright pixels suggests that the object size of several meters. The details are under investigation.

3.5 Future Operation of ASTRO-H

Based on information from several overseas organizations indicating the separation of the two SAPs from ASTRO-H, JAXA concluded that the functions of ASTRO-H could not be restored. Accordingly, JAXA ceased efforts to recover the satellite and turned to investigating the cause of the anomaly. (April 28)

- Investigation was conducted to determine the separation mechanism of the parts that were vulnerable to large rotational loads. Both of the SAPs likely broke off at their bases.

- JAXA held some hope that communication with ASTRO-H could be restored because we thought we received signals from ASTRO-H three times after object separation. However, JAXA concluded that the received signals were not from ASTRO-H based on frequency differences as a result of technological study.

4. CAUSES OF THE ANOMALY

Description on the mechanisms from the normal status to the occurrence of anomaly and the break-ups

4.1 Presumed Mechanism(Summary)

(From “Normal situation” to the “Attitude anomaly Event”, and “Objects separation”)

（1） On March 26th, attitude maneuver to orient toward an active galactic nucleus was completed as planned.

（2）After the maneuver, unexpected behavior of the attitude control system (ACS) caused incorrect determination of its attitude as rotating, although the satellite was not rotating actually. In the result, the Reaction Wheel (RW) to stop the rotation was activated and lead to the rotation of satellite.【Presumed Mechanism 1】

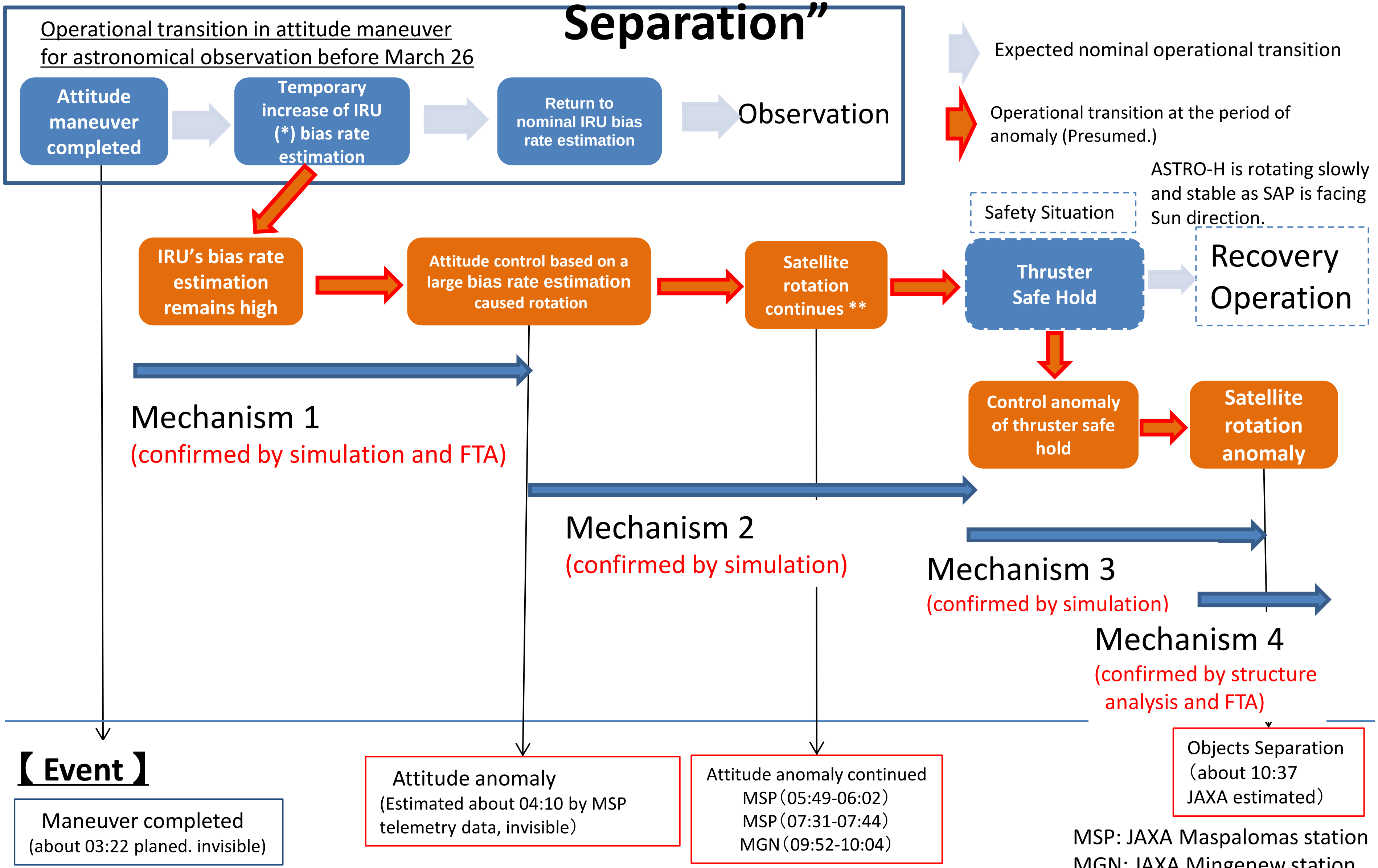
(3)In addition, unloading(*) of angular velocity by Magnetic Torquer operated by ACS did not work properly because of the attitude anomaly. The angular momentum kept accumulating in RW.【 Presumed Mechanism 2】

（4）Judging the satellite is in the critical situation, ACS switched to Safe Hold mode (SH), and the thrusters were used. At this time ACS provided atypical command to the thrusters by the inappropriate thruster control parameters. As a result, it thrusted in an unexpected manner, and it is estimated that the satellite rotation was accelerated.【 Presumed Mechanism 3】

(5)Since the rotation speed of the satellite exceeded the designed speed, parts of the satellite that are vulnerable to the rotation such as solar array paddles (SAPs), Extensible Optical Bench (EOB) and others separated off from the satellite. There is high possibility that the both SAPs had broken off at their bases and were separated. 【 Presumed Mechanism 4】

(*)Unloading：Operation to decrease the momentum kept in RW within the range of designed range.

4.1 Mechanism from “Normal Status” to “Objects Separation”



Operational transition in attitude maneuver for astronomical observation before March 26

Attitude maneuver completed → Temporary increase of IRU (*) bias rate estimation → Return to nominal IRU bias rate estimation → Observation

Expected nominal operational transition

Operational transition at the period of anomaly (Presumed.)

IRU’s bias rate estimation remains high → Attitude control based on a large bias rate estimation caused rotation → Satellite rotation continues ** → Thruster Safe Hold → Recovery Operation

Safety Situation

ASTRO-H is rotating slowly and stable as SAP is facing Sun direction.

Thruster Safe Hold → Control anomaly of thruster safe hold → Satellite rotation anomaly

Mechanism 1
(confirmed by simulation and FTA)

Mechanism 2
(confirmed by simulation)

Mechanism 3
(confirmed by simulation)

Mechanism 4
(confirmed by structure analysis and FTA)

【Event】

Maneuver completed
(about 03:22 planed. invisible)

Attitude anomaly
(Estimated about 04:10 by MSP telemetry data, invisible)

Attitude anomaly continued
MSP（05:49-06:02）
MSP（07:31-07:44）
MGN（09:52-10:04）

Objects Separation
（about 10:37
JAXA estimated）

MSP: JAXA Maspalomas station
MGN: JAXA Mingenew station

* IRU : Inertial Reference Unit

**The attitude control system in ASTRO-H is not using the sun sensor to determine satellite attitude. The system uses the estimated value calculated by the attitude control software.

Time in this page is expressed March 26 ,JST.

4.2 Mechanism 1 :

from “Normal Status” to “Attitude Anomaly”

- ASTRO-H attitude control is based on 2 instruments, Inertial Reference Unit (IRU) and Star Tracker (STT), at normal time.

- After the attitude maneuver operation was completed, ASTRO-H was scheduled to restart using STT output data. At the time of restart, IRU bias rate estimation* becomes larger than the actual one. It was expected that the correction using STT data would converge value into normal range.

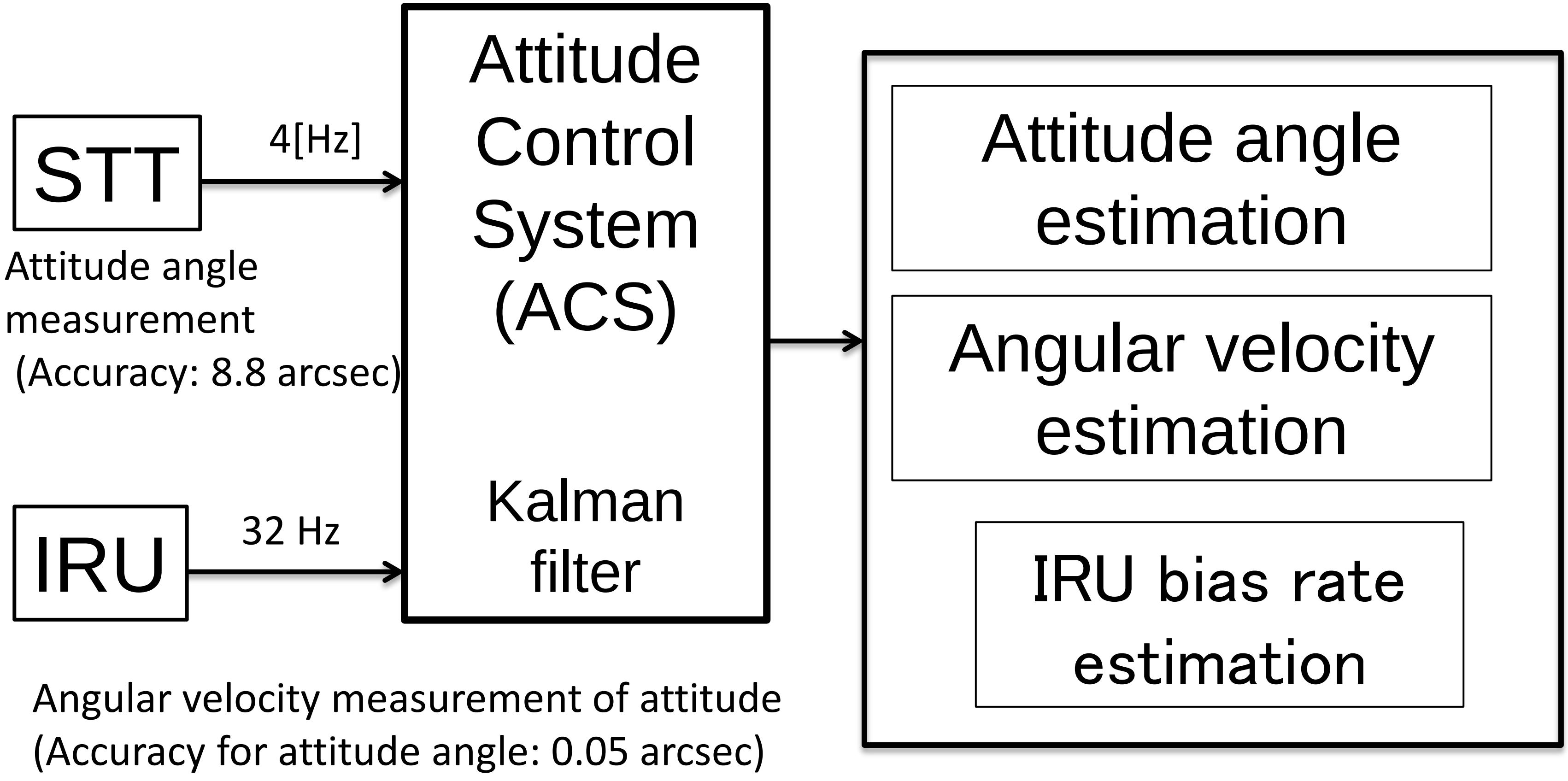
- There is a possibility that after the end of the attitude maneuver operation on March 26, STT output data had not been uploaded to ASTRO-H for some reason, resulting IRU bias rate estimation to remain larger and to continue showing anomalous value, 21.7[deg/h].

- After the maneuver, unexpected behavior of the attitude control system (ACS) caused incorrect determination of its attitude as rotating, although the satellite was not rotating actually. In the result, the Reaction Wheel (RW) to stop the rotation was activated and lead to the rotation of the satellite.

- JAXA investigated the cause for IRU rate bias to remain larger by simulation based on STT mode change using on-board software. It was confirmed that the STT behavior as shown in Page 15, made IRU bias rate remain high.

- Conducting the FTA on IRU bias rate estimation anomaly, JAXA concluded there was a very little possibility for IRU sensor anomaly and ACS computer anomaly.

Appendix A: Attitude Determination by ASTRO-H ACS



STT

4[Hz]

Attitude angle
measurement
(Accuracy: 8.8 arcsec)

IRU

32 Hz

Angular velocity measurement of attitude
(Accuracy for attitude angle: 0.05 arcsec)

Attitude Control System (ACS)

Kalman filter

Attitude angle estimation

Angular velocity estimation

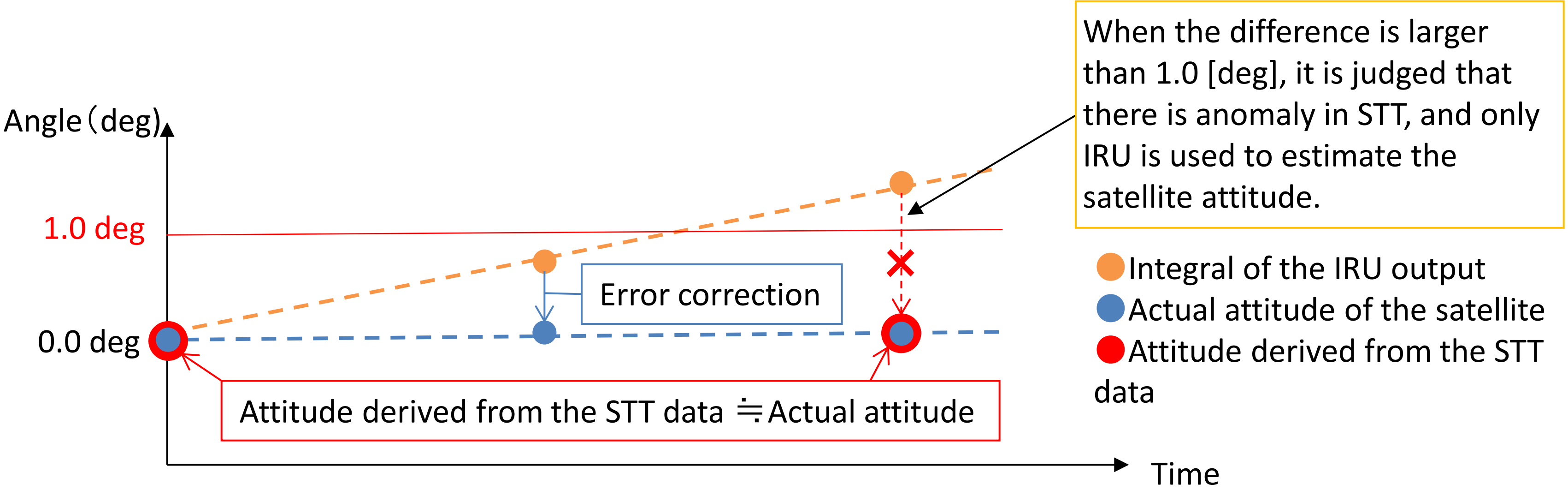
IRU bias rate estimation

Requirement for the ACS
Accuracy (X,Y: 3 arcsec; Z:12 arcsec) for attitude angle determination

1 arcsec = 1 deg/3600）

Appendix B： IRU Bias Rate Estimation

- IRU: a sensor to measure angular velocity [deg./sec] of a satellite along each axis(X, Y, and Z-axis)
- IRU values are integrated to determine the attitude of the satellite in the case of IRU only estimation,
  ex.) measurement：0.1[deg./sec], estimated attitude after 10 sec: 0.1 × 10[sec]=1.0[deg.]）.
- The slight offset errors in the measured angular velocity are accumulated by the time integration.
  ex.) Error in the measurement：0.01[deg./sec] Attitude error after 10 sec：0.01 × 10=0.1deg）
- Comparing the attitude estimation with the STT of higher accuracy, the error trend of the IRU (shown in the orange line in the lower figure) is derived
- This error trend (the bias rate estimation) enables us to estimate the satellite's attitude accurately even if the STT data are not available.



When the difference is larger than 1.0 [deg], it is judged that there is anomaly in STT, and only IRU is used to estimate the satellite attitude.

Attitude derived from the STT data ≒Actual attitude

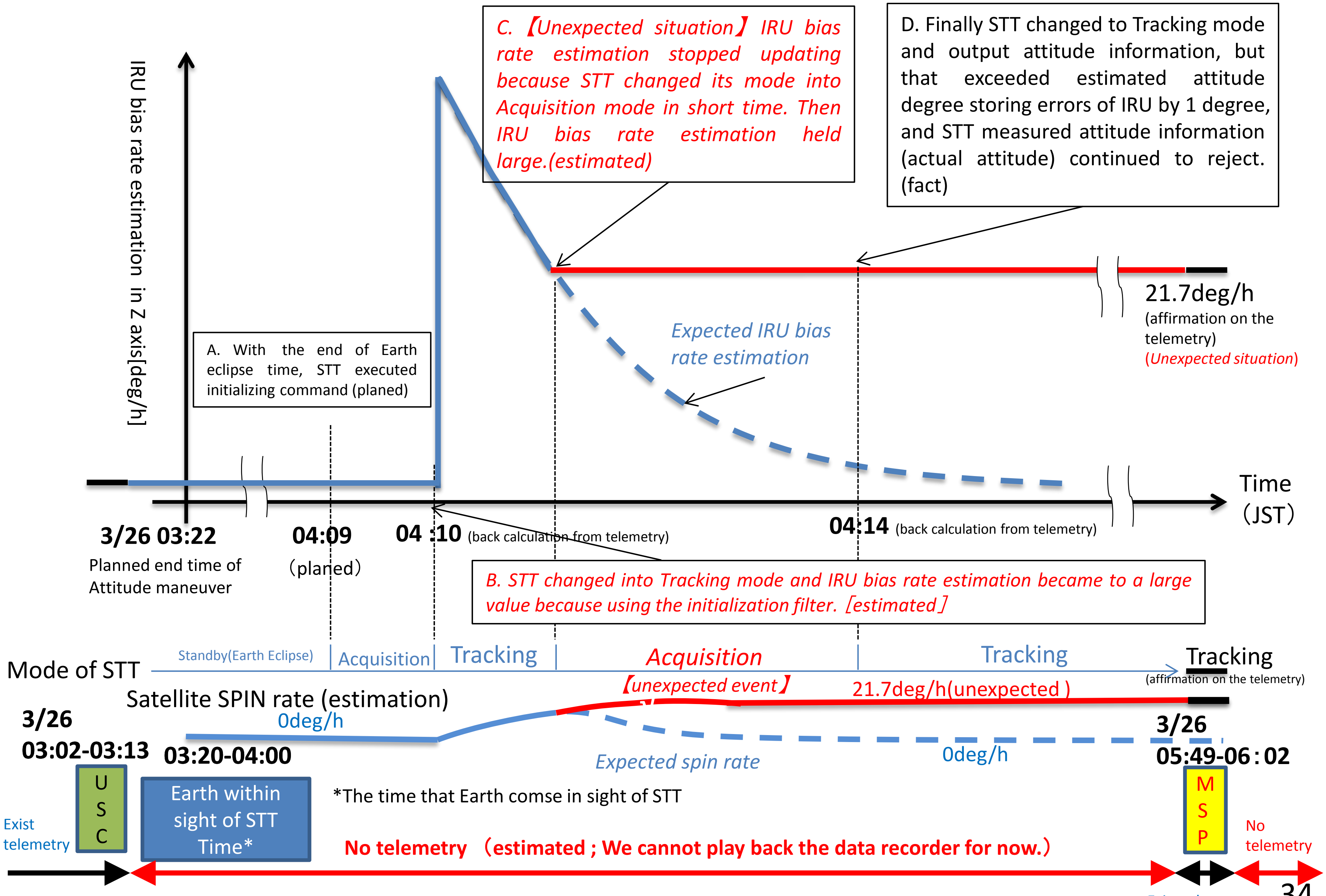
● Integral of the IRU output
● Actual attitude of the satellite
● Attitude derived from the STT data

Figure : the sketch of the process.

※STT: Optical device to estimate the attitude of a satellite based on stellar positions. A series of complicated calculation is required to derive the attitude from the STT data, and the frequency of its output is low. Contrary, the IRU 's output is speedy, because the derivation method of the attitude is simple.

（note）This is just a image to understand easily. This image differs from actual process.

4.2 IRU Bias Rate behavior



A. With the end of Earth eclipse time, STT executed initializing command (planed)

B. *STT changed into Tracking mode and IRU bias rate estimation became to a large value because using the initialization filter. [estimated]*

C. *【Unexpected situation】 IRU bias rate estimation stopped updating because STT changed its mode into Acquisition mode in short time. Then IRU bias rate estimation held large.(estimated)*

D. Finally STT changed to Tracking mode and output attitude information, but that exceeded estimated attitude degree storing errors of IRU by 1 degree, and STT measured attitude information (actual attitude) continued to reject. (fact)

*The time that Earth comse in sight of STT

No telemetry （estimated ; We cannot play back the data recorder for now.）

USC: JAXA Uchinoura station

4.3 Mechanism 2：

from the attitude anomaly to the continuously rotation of attitude

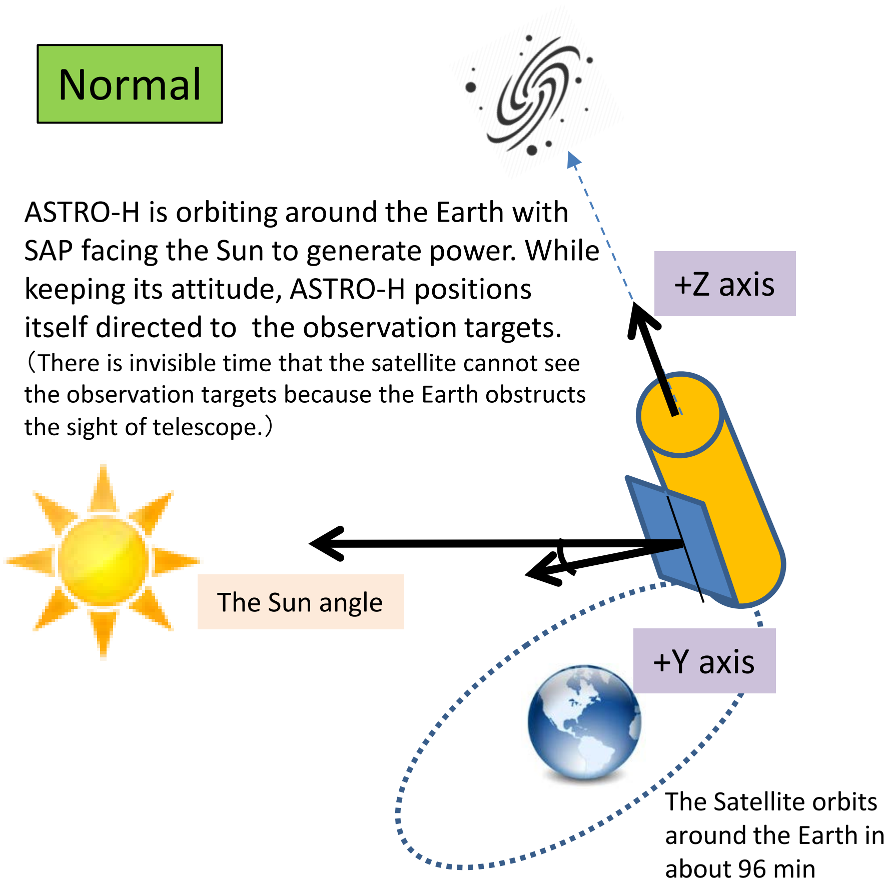
- As shown in the mechanism 1, ASTRO-H made incorrect determination of its attitude as rotating, although the satellite was not rotating actually. ACS does not use the sun sensor to determine its attitude, and anomaly was not able to be detected. As a result, the rotation continued. 【Appendix C】
- At this time, it is confirmed that the unloading process of angular momentum in RW by Magnetic Torquer operating in parallel to the rotation control did not work properly because of the attitude anomaly, then angular momentum was accumulated in RW.
- It is confirmed that, by the further analysis of the telemetry data of MGN at 09:50-10:04, the angular momentum in RW was rising near the design limitation (Telemetry 112[Nms], Limitation: 120[Nms])
- JAXA estimated the accumulated angular momentum in case of attitude anomaly by computer simulation. Then it is confirmed that the estimated angular momentum was almost the same as the telemetry data.

*FDIR： Fault Detection Isolation and Reconfiguration

**Unloadeing：Operation to adjust the RW rotation frequency in normal range by using a magnetic torquer or RCS thuruster

***Accumulation of angular momentum：Corresponding to an increase of rotation frequency

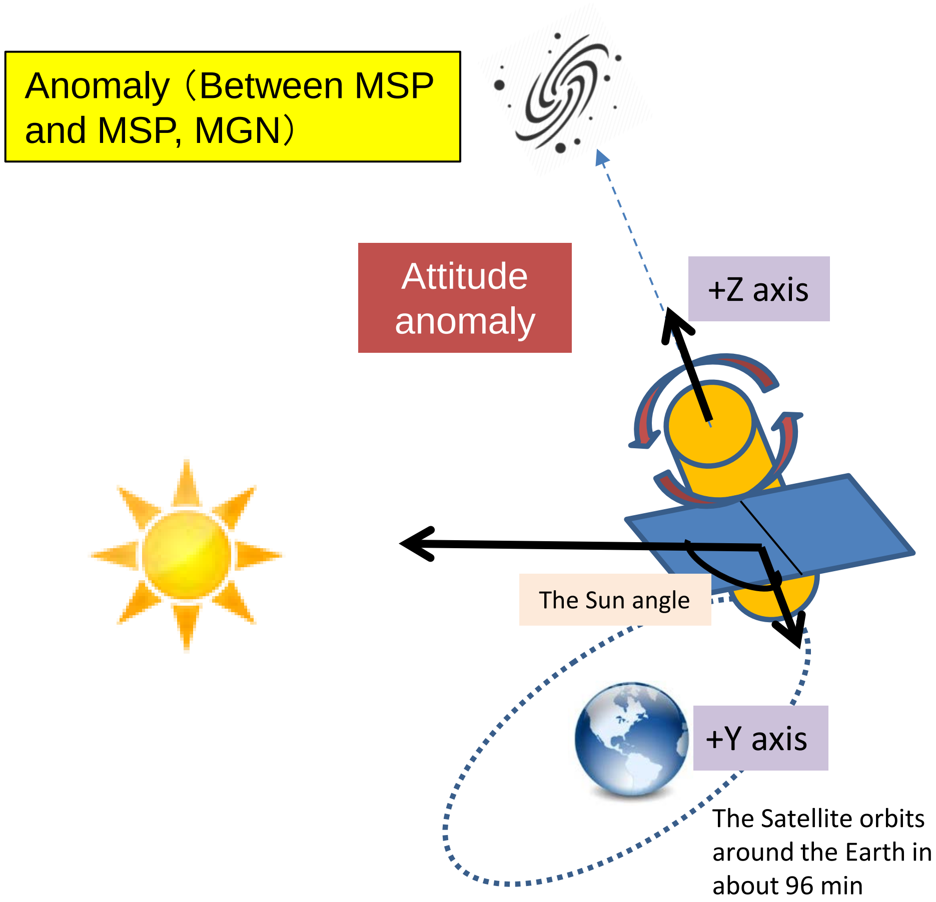
Appendix C：
Schematic of ASTRO-H behavior under attitude anomaly



Normal

ASTRO-H is orbiting around the Earth with SAP facing the Sun to generate power. While keeping its attitude, ASTRO-H positions itself directed to the observation targets.
（There is invisible time that the satellite cannot see the observation targets because the Earth obstructs the sight of telescope.）

The nominal angle between satellite +Y axis and the Sun angle is within ±30 degrees.



Anomaly（Between MSP and MSP, MGN）

The IRU estimated error value continues, and ASTRO-H began to rotate along Z axis about 21.7 degree/hour slowly. The Sun angle at a time of the last telemetry reception at MGN was about 123 degrees.

4.4 Mechanism 3：

from the attitude rotation to the rotation anomaly

- When exceeding the angular momentum limitation (120 Nms) accumulated in the RW, the ACS concluded that there was anomaly in the control by the RW, then shifted to a mode that controls its attitude using thrusters (Thruster Safe Hold Mode: RCS(Reaction Control System) SH(Safe Hold)).
- In the RCS SH, the satellite conducts the attitude recovery operation using thrusters by detecting the Sun【Appendix D】
- There was injection control anomaly with inappropriate RCS control parameter. As a result, the velocity of the rotation increased.【Appendix E】
- JAXA conducted simulation study on RCS behavior by using inappropriate RCS control parameter. The simulation showed the rotation acceleration behavior and the rotation speed finally went up to induce the break-up of SAP.【Appendix F】
- The attitude angle, the angular velocity and the sun angle confirmed by simulations were described. 【Appendix G】

Appendix D: RCS Safe Hold (SH)

The RCS SH of ASTRO-H proceeds through the following steps.

(1) CSAS, IRU, AOCP, and RCS of ACS are switched from the primary system to the redundant system.

(2) Rate dump is performed by using RCS when IRU detects an angular velocity of >0.08 deg/s.

(3) The satellite tries to detect the sun by using CSAS, IRU, and RCS. If this fails, the satellite itself rotates its body rotate around the X-, Y- and Z-axes in turn to search for the sun.

(4) After detecting the sun, the satellite captures the sun in the direction of the +Y-axis, and rotates at a rate of 0.25 deg/s to minimize propellant consumption.

In the following two cases, the satellite rotates at a slow rate of −0.05 deg/s around the X-axis and waits until leaving the shade:

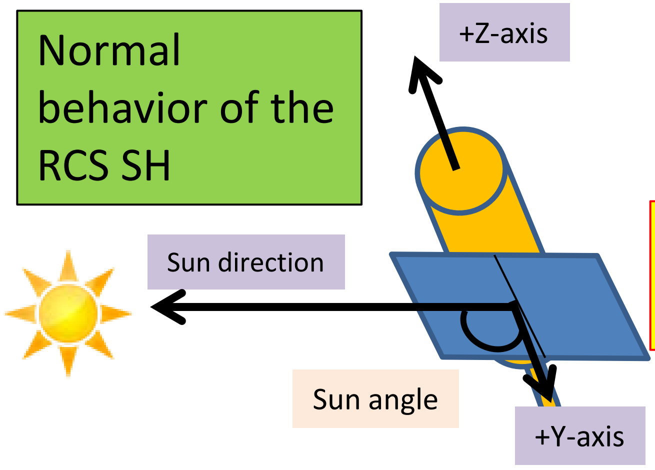
(1) The satellite is in shade when the search for the sun starts.

(2) AOCP judges that search for the sun cannot be completed before leaving the sunlight. (This is because of limits on sunlight incident on the instruments.)

Appendix E: Schematic View of the Satellite's Behavior at Anomalies 3 and 4

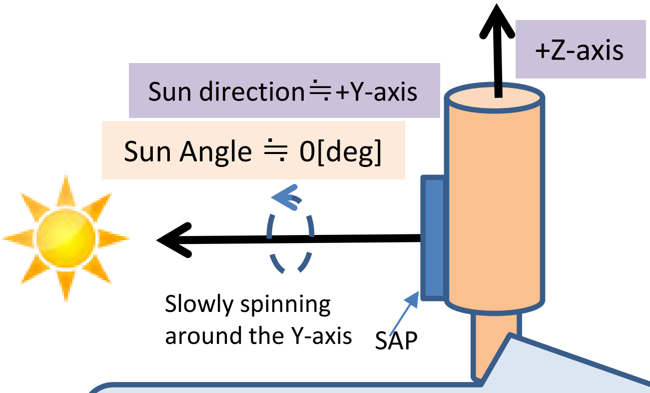
From 10:04 March 26th (after MGN pass) to 10:37 (the break-up time estimated by JAXA

Normal behavior of the RCS SH



Reaches the upper limit of RW rotation frequency

Terminates the observation (gives up directing itself toward the object), and switches to RCS SH mode.



SH attitude

Dynamically stable and electric power ensuring attitude. The satellite waits for recovery commands from the ground.

Estimated behavior of the RCS SH in this anomaly

Same status as in the upper left figure

Estimated that the RW rotation frequency reached its upper limit.

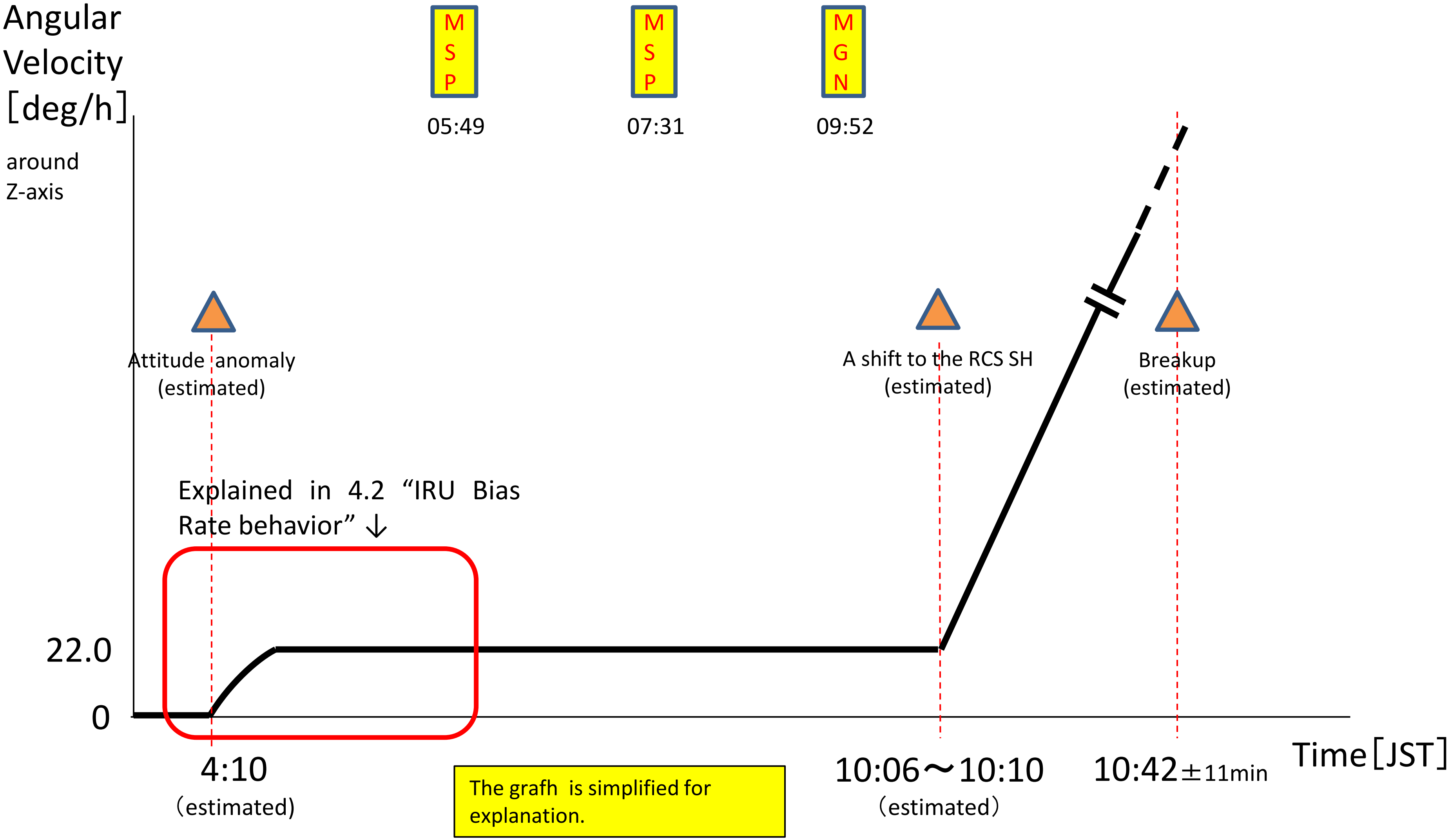
Estimated that the satellite terminated the observation and switched to the RCS SH mode.

Estimated that a thruster fired in an unexpected direction due to inappropriate control parameters.

- The angular velocity of the satellite is thought to have increased.
- The parts (SAPs and EOB) that were vulnerable to large rotational loads broke off.

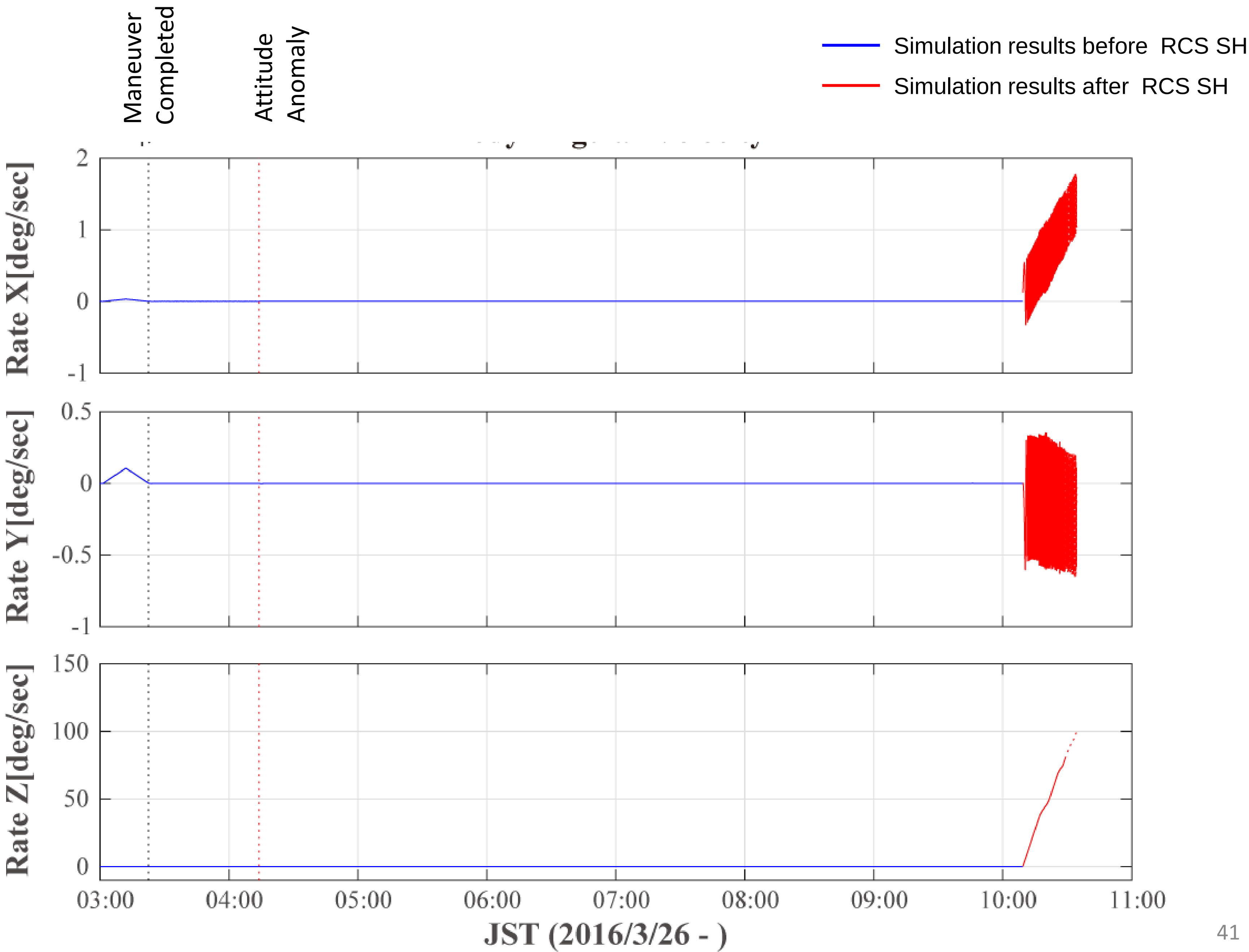
Appendix F: Behavior on ASTRO-H angular velocity around Z-axis

（from the end of the Attitude Maneuver）

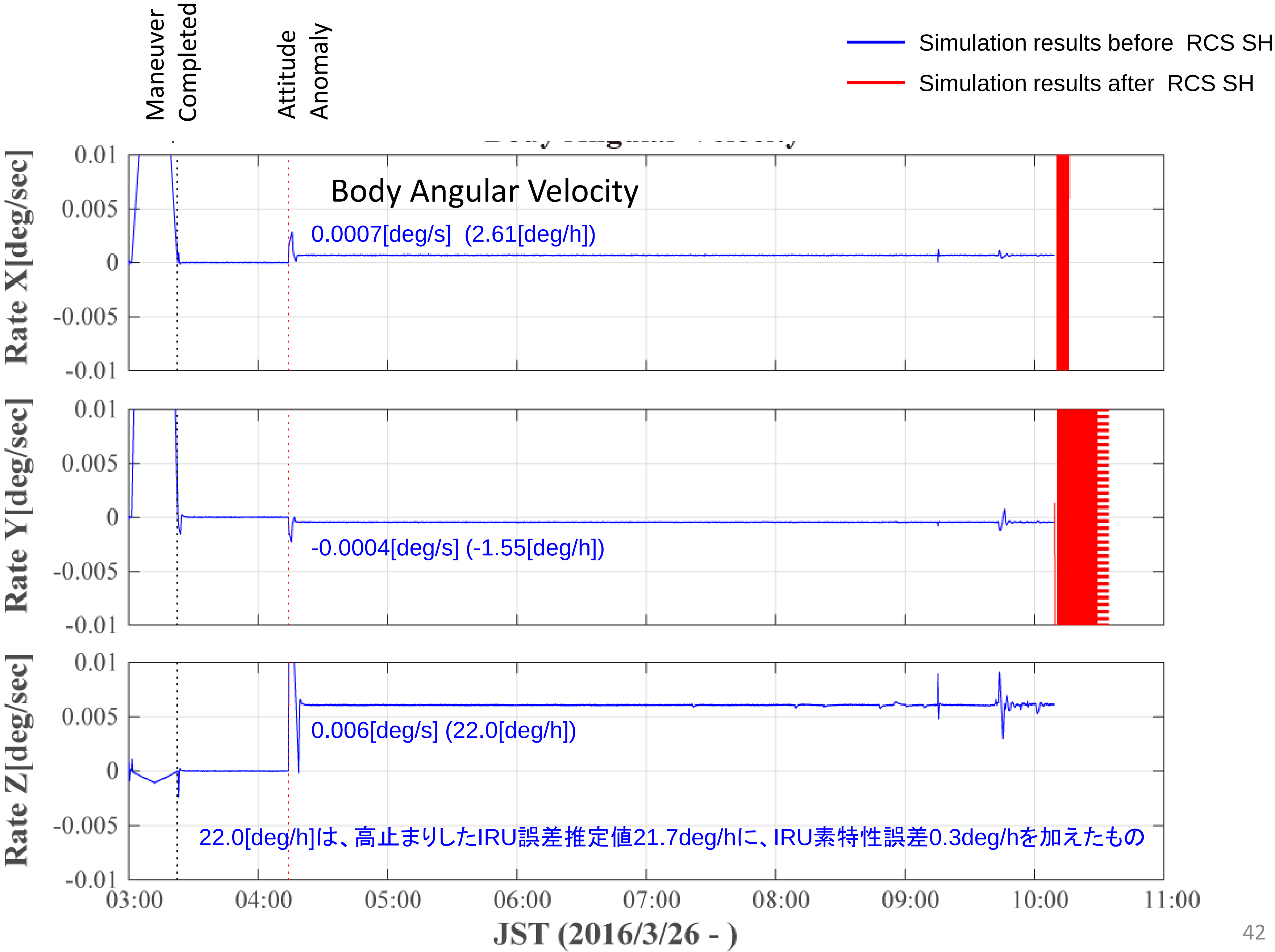


The grafh is simplified for explanation.

Appendix G: Attitude Angular Velocity of ASTRO-H (The Whole Scale)

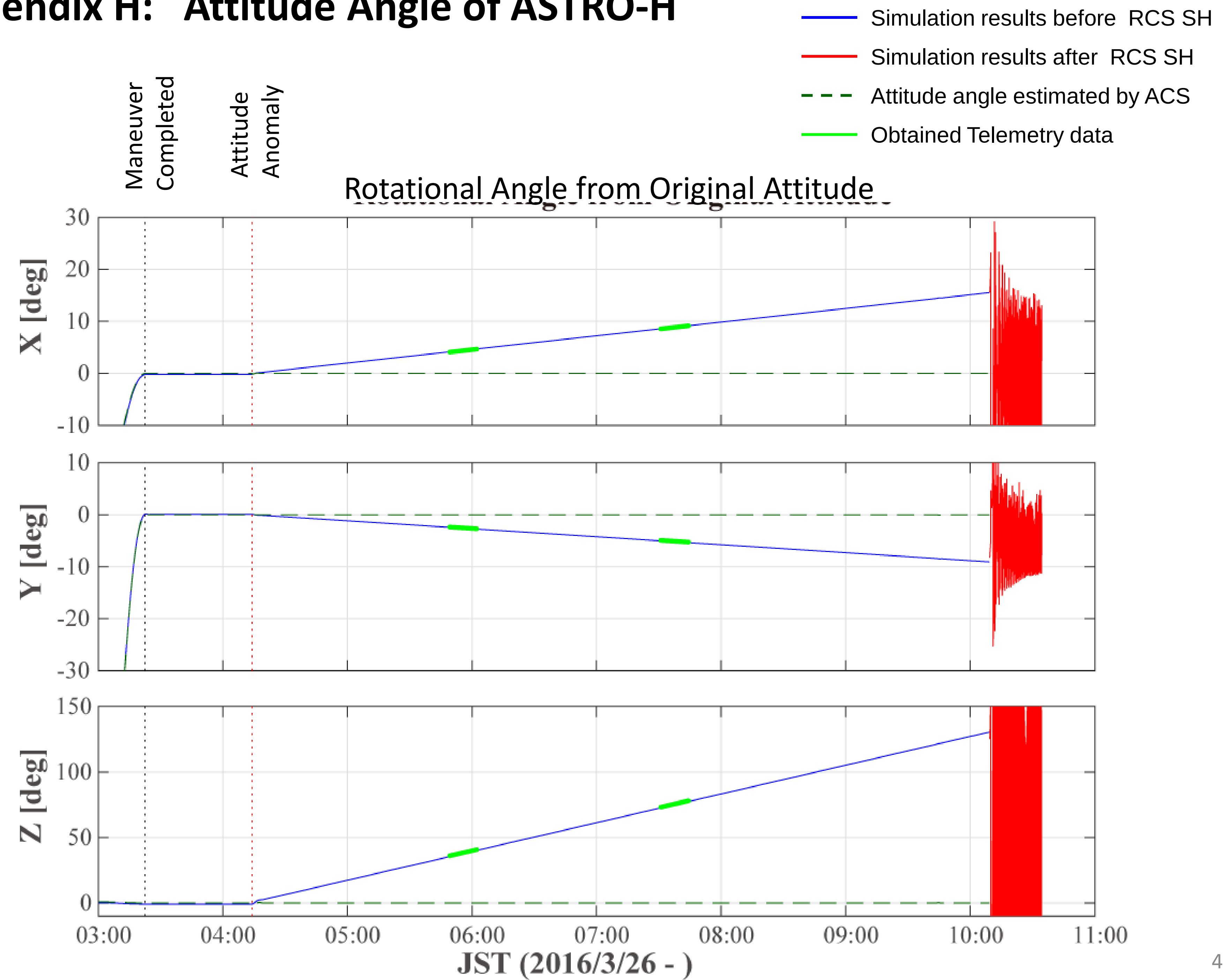


Appendix G: Attitude Angular Velocity of ASTRO-H (Big Scale)

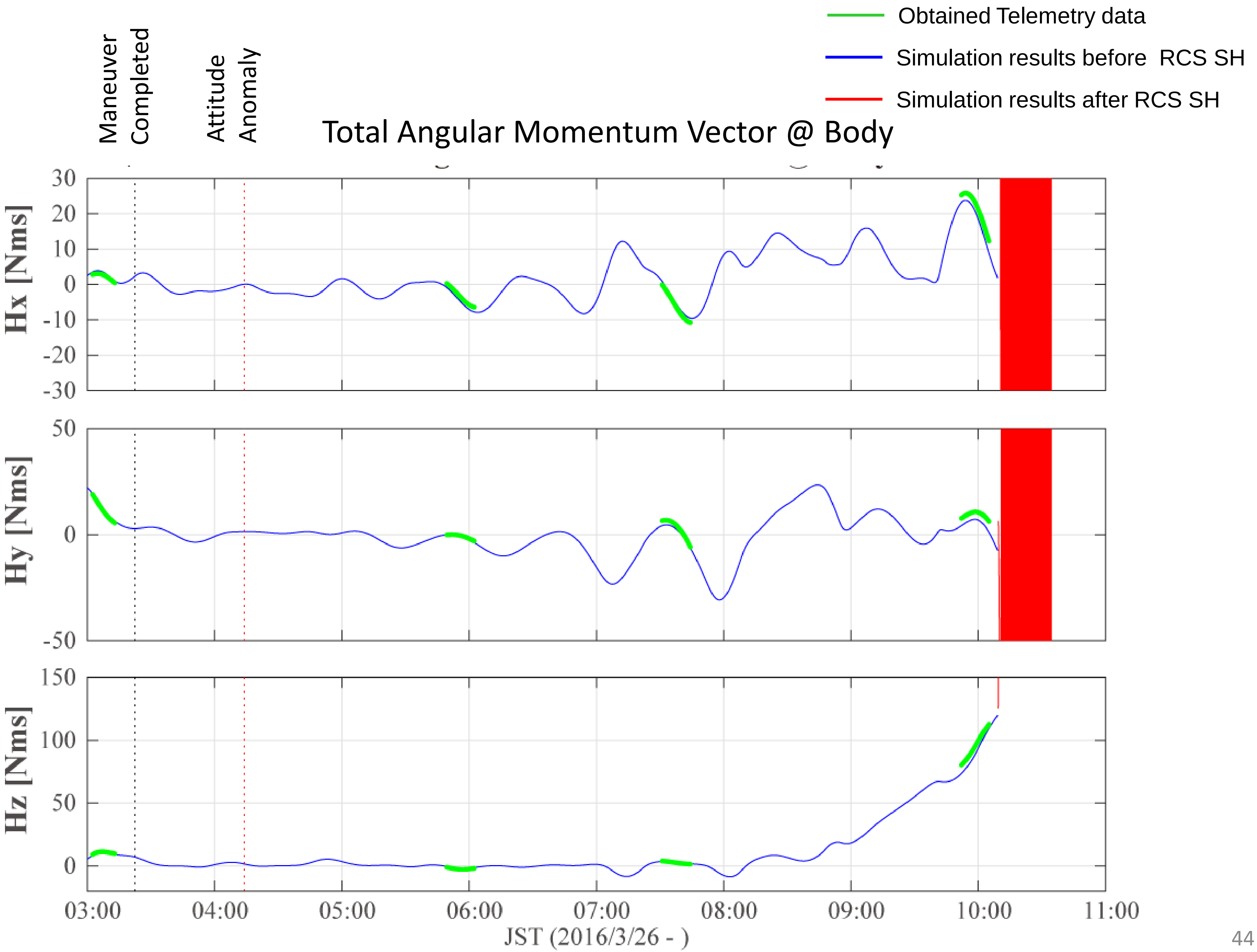


22.0[deg/h]は、高止まりしたIRU誤差推定値21.7deg/hに、IRU素特性誤差0.3deg/hを加えたもの

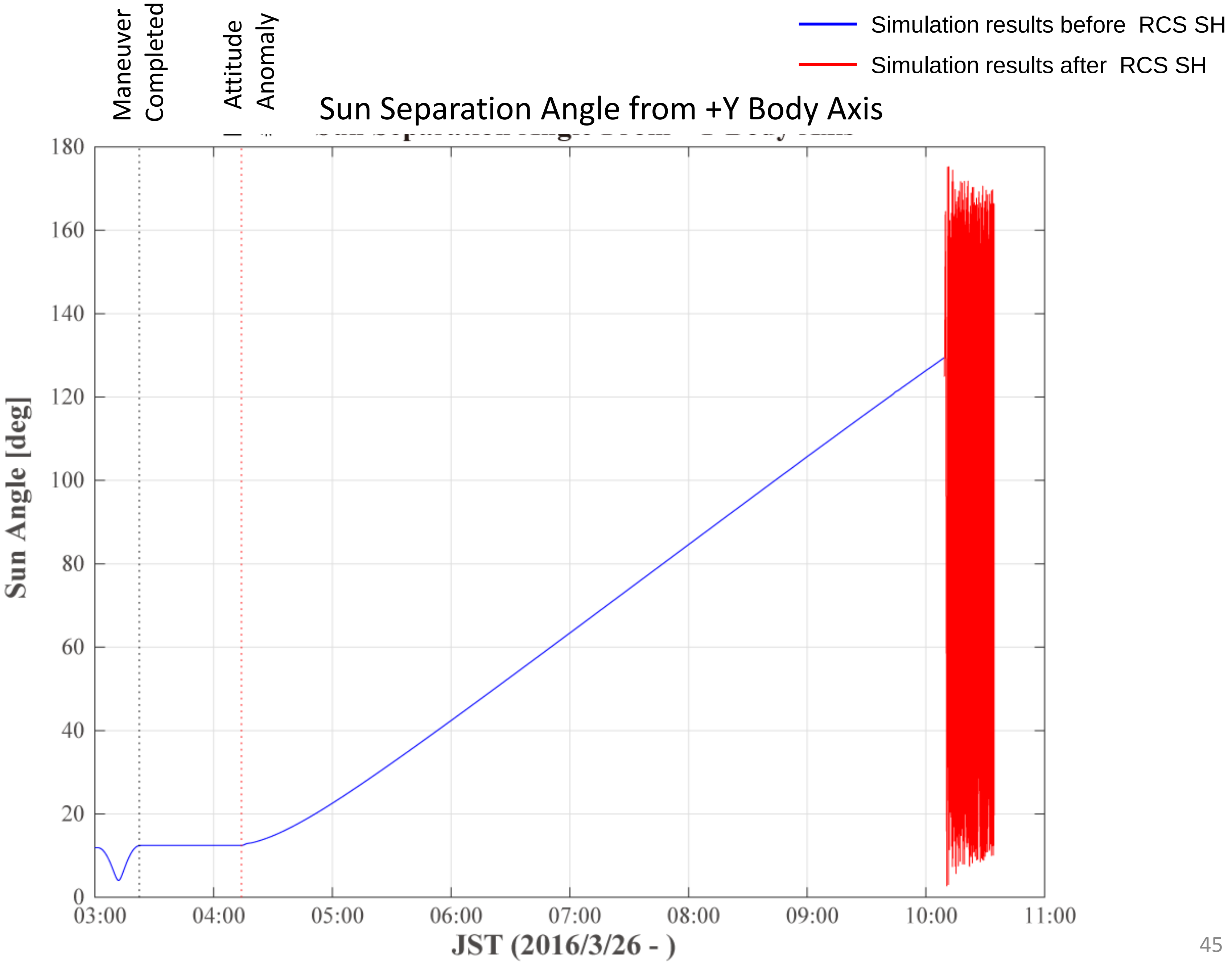
Appendix H: Attitude Angle of ASTRO-H



Appendix H: Total Angular Momentum of ASTRO-H



Appendix H: Angle between the sun direction and +Y axis



4.5 Anomaly Mechanism 4: From Spinning to Breakup

- JAXA estimated that the increase in the angular velocity of the satellite resulted in separation of the parts that were vulnerable to large rotational loads, such as the SAPs and EOB.
- According to investigation results, it is more likely that both the SAPs broke off at their base than that a part of the SAPs separated.
  - Detailed structural analysis of the SAPs by the finite element method showed that the SAP base was the part most vulnerable to rapid rotation.
  - The critical angular velocity for breaking of the SAP base was roughly consistent with that derived from ground-based observations conducted by observatories that JAXA asked for support.
- JAXA conducted the same analysis for EOB and concluded that EOB and the instruments attached at the top also separated from the main body. (Supplement 1)

Appendix I

The spacecraft experiences heavy loads at liftoff. The SAP and EOB were folded up when ASTRO-H was launched, and the both components were extended on orbit. Thus, they were more vulnerable than other components to external loads. The table below shows simulation results on the upper limit of angular velocity tolerance. Results for rotation around the Y-axis are omitted, because the simulations showed the upper limit was much larger for the Y-axis than for the other axes.

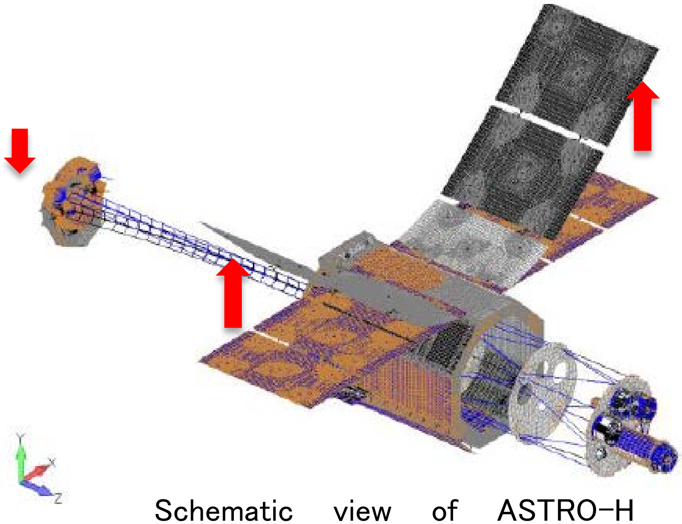
The figure below illustrates the distortion of an SAP when the satellite rotates around the Z-axis. It can be seen that the SAP base is subjected to a large bending moment.

As a result of rotation, EOB is pulled by the instruments mounted on it and by the HXI plate. The tensile load acts almost evenly for each step of EOB, leading to similar threshold angular velocities around the X- and Y-axes.

Approximate angular velocity thresholds (ω_max) for breakup

Part	Rotation Axis	ω_max [deg/s]	Part
SAP	Z	150	SAP base
	X	150	SAP base
EOB	Z	125	Satellite side end of EOB
	X	90	EOB (each step)
	Y	90	EOB (each step)

Note: Axes are defined in Section 2.3.



Schematic view of ASTRO-H rotating around the Z-axis

4.6 Estimated Status of the Satellite

- Rapid spinning of the main body of ASTRO-H
- Separation of both SAPs
- Separation of EOB with HXI attached to the tip
- Depletion of the battery

Considering the information above, JAXA concluded that the satellite's functionality could not be restored and ceased recovery activities. (April 28)

- Observations showed that among the objects that separated from ASTRO-H, two had faster decreases in altitude and reentered the atmosphere on April 20 and 24. For the following reasons, JAXA estimated that these two objects burned up in the atmosphere.

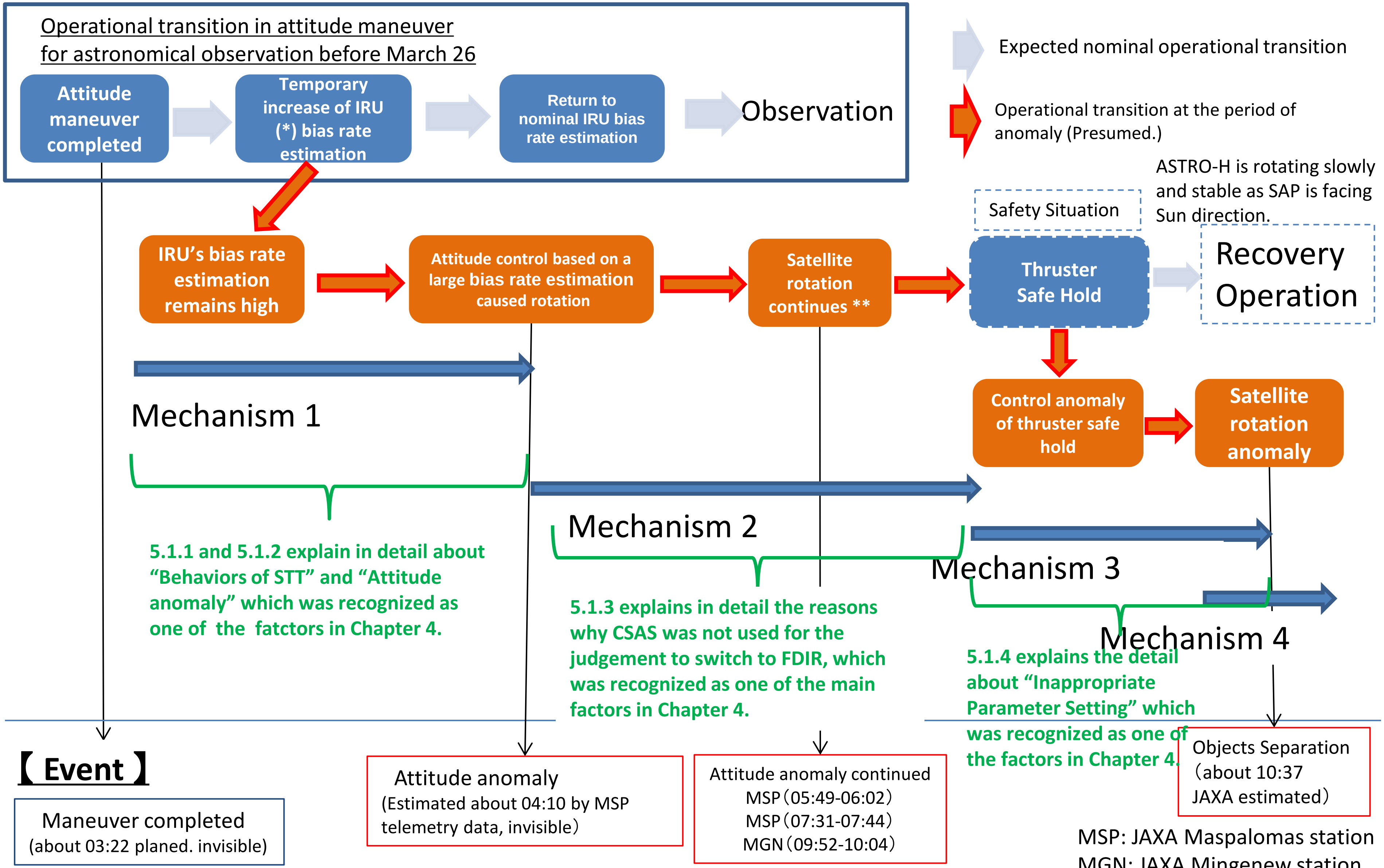
- Air heating would melt most of the satellite materials, except for special ones such as titanium alloy.
- Only the satellite's fuel tank (made of titanium alloy) would not be melted.
- These two objects that descended fastest are thought to have large air resistance relative to their mass, such as heat insulators attached to the satellite surface. Thus, they were not expected to be the fuel tank.

5. FACTORS CONTRIBUTING TO THE ANOMALY

Section 5.1 describes the direct technical factors contributing to the anomaly that was described in Chapters 1 to 4.

Section 5.2 describes analysis results at each phase of design, production/test, and operation to identify problems leading to the technical factors described in Section 5.1.

Mechanism from “Normal Status” to “Objects Separation”



Operational transition in attitude maneuver for astronomical observation before March 26

Attitude maneuver completed

Temporary increase of IRU (*) bias rate estimation

Return to nominal IRU bias rate estimation

Observation

Expected nominal operational transition

Operational transition at the period of anomaly (Presumed.)

ASTRO-H is rotating slowly and stable as SAP is facing Sun direction.

Safety Situation

IRU’s bias rate estimation remains high

Attitude control based on a large bias rate estimation caused rotation

Satellite rotation continues **

Thruster Safe Hold

Recovery Operation

Control anomaly of thruster safe hold

Satellite rotation anomaly

Mechanism 1

5.1.1 and 5.1.2 explain in detail about “Behaviors of STT” and “Attitude anomaly” which was recognized as one of the fatctors in Chapter 4.

Mechanism 2

5.1.3 explains in detail the reasons why CSAS was not used for the judgement to switch to FDIR, which was recognized as one of the main factors in Chapter 4.

Mechanism 3

Mechanism 4

5.1.4 explains the detail about “Inappropriate Parameter Setting” which was recognized as one of the factors in Chapter 4.

【Event】

Maneuver completed
(about 03:22 planed. invisible)

Attitude anomaly
(Estimated about 04:10 by MSP telemetry data, invisible)

Attitude anomaly continued
MSP（05:49-06:02）
MSP（07:31-07:44）
MGN（09:52-10:04）

Objects Separation
（about 10:37
JAXA estimated）

MSP: JAXA Maspalomas station
MGN: JAXA Mingenew station

* IRU : Inertial Reference Unit

**The attitude control system in ASTRO-H is not using the sun sensor to determine satellite attitude. The system uses the estimated value calculated by the attitude control software.

Time in this page is expressed March 26 ,JST.

5.1.1 STT Behavior（1/3）

(1) Facts

JAXA has confirmed the following events.

1. 3/25UT
   → a) 18:22: Planned time of the completion of the maneuver
   → b) 19:00: End of the period when STT obstructed by Earth
   → c) Pass above the South Atlantic Anomaly (SAA)
   → d) 19:09: End of STT standby operation, implementation of the STT acquisition command
   → e) 19:10：STT switched from acquisition mode to tracking mode, and the Kalman filter reset (estimated from telemetry)
   → g) 19:14 onward: STT remains in tracking mode (estimated from telemetry) ⇒ Event A

   - f): At least one time between e) and g), the STT mode returned from tracking mode to acquisition mode.
   - STT returned to tracking mode. Thus, STT did not switch to emergency mode and stayed in tracking mode due to its design and setup.

JAXA estimated the above event (STT Event A) occurred.

5.1.1 STT Behavior (2/3)

(1) Facts (continued)

2. Evaluation results for on-orbit data indicate the occurrence of the following events during operations from launch to Event A
   - Event B: STT2 temporarily returns from tracking mode to acquisition mode (15 events)
   - Event C: Quaternion validity flag (*1) becomes invalid while STT is in tracking mode (3 events)
   - Event D: Emergency return from tracking mode to acquisition mode (1 event)
3. Since Feb 28, the satellite was operated in STT standby mode as a countermeasure to Event D when Earth obscured the STT field of view.
4. These events were not significantly different between STT1 and STT2.
5. The STT on board ASTRO-H was newly developed based on the heritage of Japanese STTs to date.

(*1) STT telemetry indicating the validity of the attitude information from STT. The Kalman filter includes the STT data only when the flag indicates the information is valid.

5.1.1 STT Behavior (3/3)

(2) Direct factors (estimation)

- There is a possibility that other STTs return from tracking mode to acquisition mode depending on the status of the STT optical system.
- JAXA estimated that STT Event A occurred on March 26, as described below, based on information from telemetry data in 19 other cases (described in "Reference") and the results of analyzing the field of view (FOV) and the STT processing software.
  - STT Event B (2 events) and STT Event C (4 events in total): Under the initial threshold value on window pixel size, there were few bright stars available for estimating the attitude rate. Accordingly, the errors in the attitude rate estimation increased and the transition from acquisition mode to tracking mode was unstable. Consequently, the tracking was terminated.
  - STT Event A of March 26: Analysis of the FOV of STT indicated that Event A occurred in the same situation and had the same causes as the four cases above.
- The threshold value on window pixel size was set to the default and needed to be adjusted. On-orbit optimization was planned for after March 26.

5.1.2 AOCS Design (Attitude Anomaly) (1/3)

(1) Facts: JAXA has confirmed the following events on March 26.

- 03:02 – 03:13 after the USC pass: The Kalman filter was reset by time-line commands after completion of the maneuver.

- 05:49 - 06:02 in the MGN pass: The IRU bias rate was maintained at 21.7 deg/h. JAXA confirmed a decrease in power generation.

- 09:52 – 10:04 in the MGN pass (confirmation required): The rejection of STT data continued, as did the rotation of the satellite at about 21.7 deg/h (estimation from STT data), the absence of the sun (SAPs were not directed toward the sun), and changes in the temperature distribution of the satellite (a change in attitude is the estimated cause).

5.1.2 AOCS Design (Attitude Anomaly) (2/3)

(2) Direct factors (estimation)

JAXA estimates the following three factors caused the IRU bias rate to remain high and led to the attitude anomaly.

a. Parameter setting where the IRU bias rate temporally took a high value when the Kalman filter was reset after a maneuver.

To maximize observation time, it was necessary to complete calculations for attitude determination as soon as possible after the completion of a maneuver. Thus, the Kalman gain was designed to take a rather high value when the Kalman filter was reset after a maneuver. This resulted in a period in which the IRU bias rate took a high value during attitude determination.

Note that the same behavior happened before the events on March 26. However, in the previous cases, the conversion time was short, as planned, because the STT data were included continuously.

b. Design concept where the two STT were not used as a redundancy system

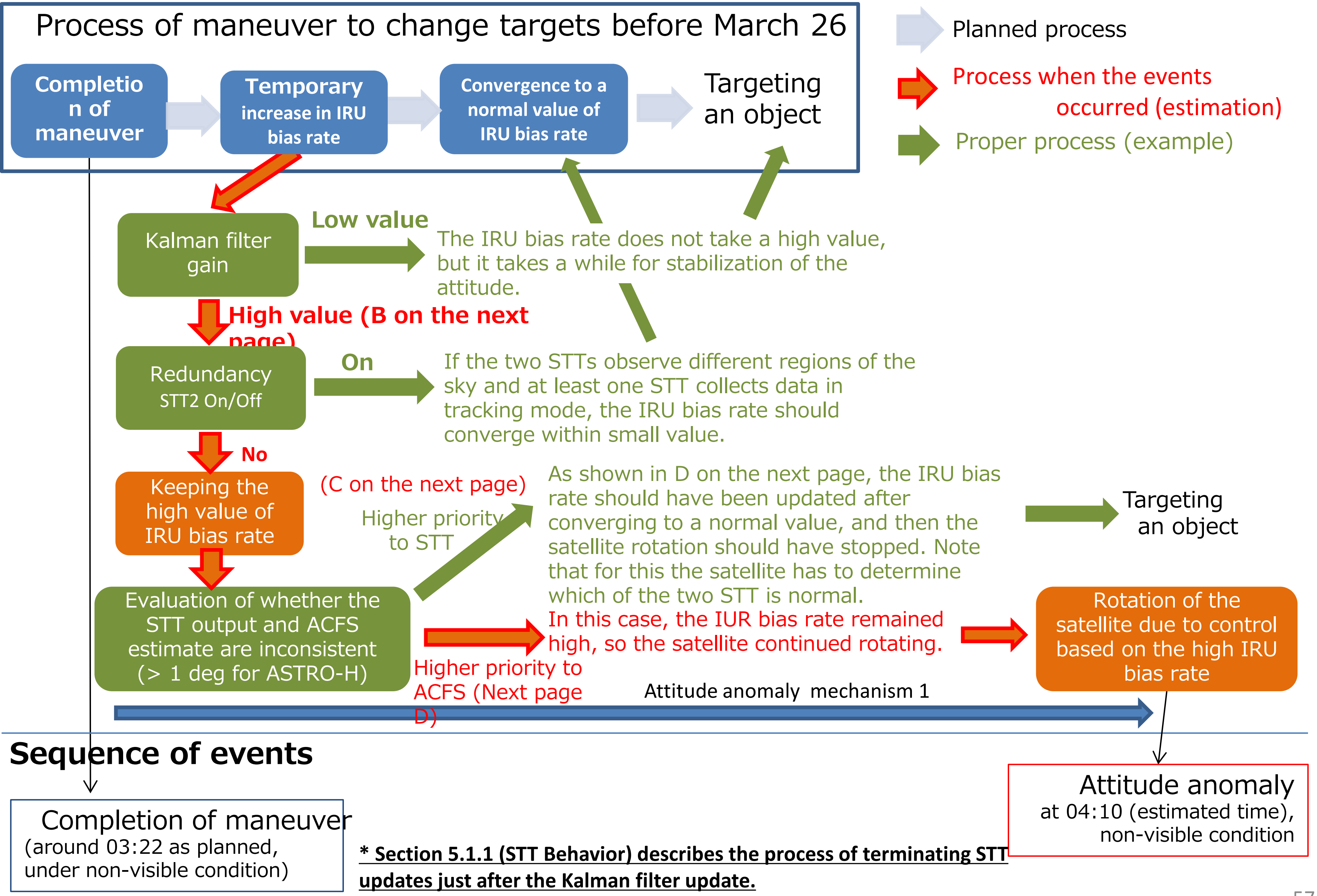
ASTRO-H was equipped with two STT. When one of the two STT was not available, the satellite was configured such that neither STT was used and satellite attitude determination relied solely on the estimates by ACFS which were derived from the IRU output. This configuration has the benefit of avoiding attitude variations lasting minutes and maximizing observation time at a stable attitude. Consequently, the primary STT was not switched to the redundant one and the IRU bias rate remained high, even when STT returned to acquisition mode just after switching to tracking mode. Note that only one of the two STT was used on March 26 because on-orbit adjustments of the STT parameters were not complete.

5.1.2 AOCS Design (Attitude Anomaly) (3/3)

c. Configuration to ignore estimates by STT that were different from estimates by ACFS

STT determines the attitude at particular times, whereas ACFS calculates attitude continuously. ASTRO-H was configured to use the ACFS estimate when the difference between the STT and ACFS estimates exceeded 1 deg. There are two reasons for this. First, sporadic noise affects the accuracy of attitude determination by STT and the adopted configuration enables avoidance of this problem. Second, the estimate by IRU is comparatively accurate even if STT estimates are not included. Thus, it was decided that operation could be flexibly handled from the ground. However, in this instance, the IRU bias rate was fixed at a higher value than planned and the difference in the attitude estimates by STT and ACFS had already exceeded 1 deg. As a consequence, the measurements by STT continued to be rejected.

Anomaly (1): Occurrence of Attitude Anomaly (Rotation) - AOCS Design



Process of maneuver to change targets before March 26

Completion of maneuver → **Temporary increase in IRU bias rate** → **Convergence to a normal value of IRU bias rate** → Targeting an object

Planned process

Process when the events occurred (estimation)

Proper process (example)

Kalman filter gain

Low value → The IRU bias rate does not take a high value, but it takes a while for stabilization of the attitude.

High value (B on the next page)

Redundancy STT2 On/Off

On → If the two STTs observe different regions of the sky and at least one STT collects data in tracking mode, the IRU bias rate should converge within small value.

No

Keeping the high value of IRU bias rate

(C on the next page)

Evaluation of whether the STT output and ACFS estimate are inconsistent (> 1 deg for ASTRO-H)

Higher priority to STT → As shown in D on the next page, the IRU bias rate should have been updated after converging to a normal value, and then the satellite rotation should have stopped. Note that for this case the satellite has to determine which of the two STT is normal. → Targeting an object

Higher priority to ACFS (Next page D) → In this case, the IUR bias rate remained high, so the satellite continued rotating. → Rotation of the satellite due to control based on the high IRU bias rate

Attitude anomaly mechanism 1

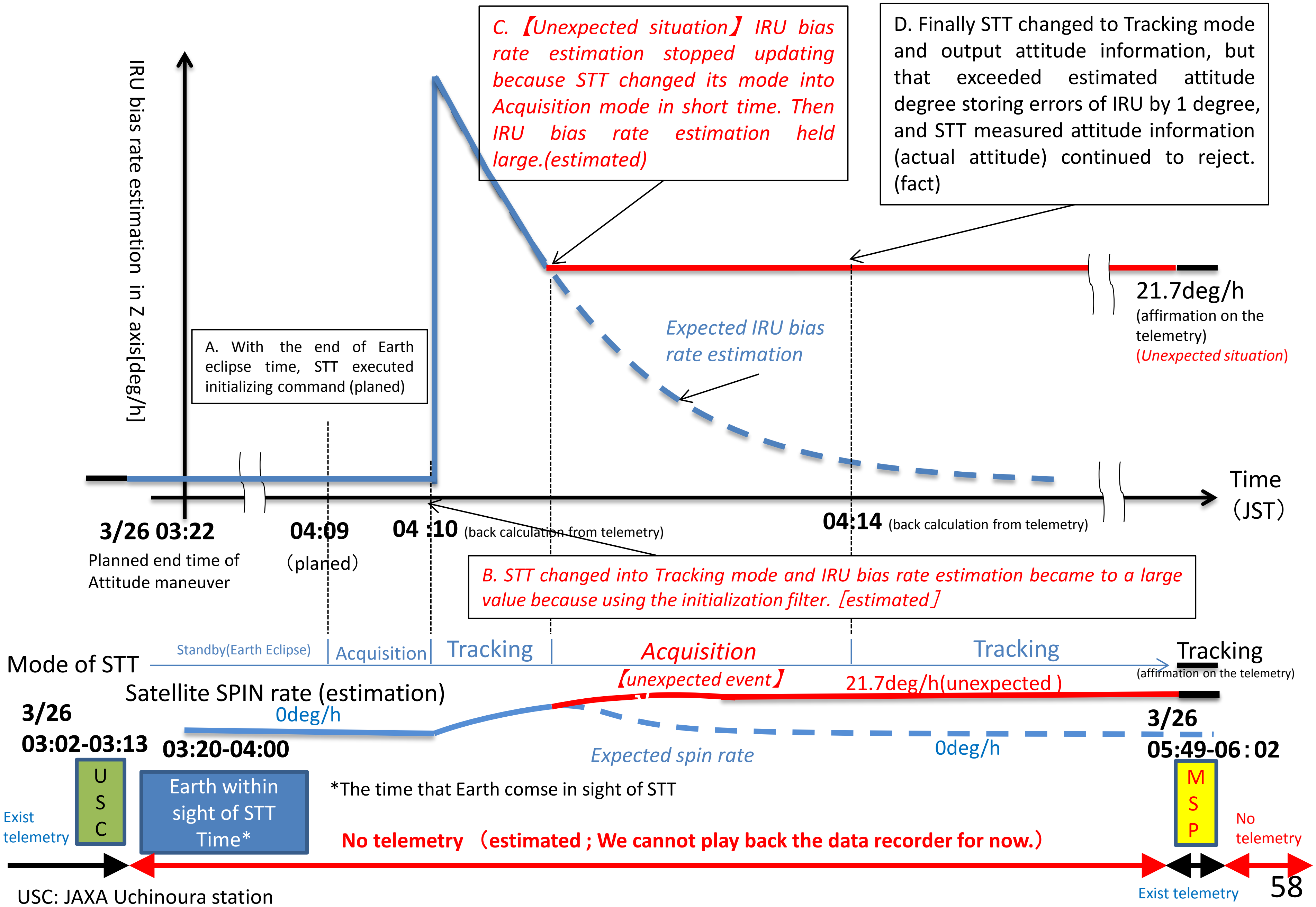
Sequence of events

Completion of maneuver
(around 03:22 as planned, under non-visible condition)

Attitude anomaly
at 04:10 (estimated time), non-visible condition

*** Section 5.1.1 (STT Behavior) describes the process of terminating STT updates just after the Kalman filter update.**

Mechanism1: from the “Normal Status” to “Attitude Anomaly”



A. With the end of Earth eclipse time, STT executed initializing command (planed)

B. STT changed into Tracking mode and IRU bias rate estimation became to a large value because using the initialization filter. [estimated]

C. 【Unexpected situation】 IRU bias rate estimation stopped updating because STT changed its mode into Acquisition mode in short time. Then IRU bias rate estimation held large.(estimated)

D. Finally STT changed to Tracking mode and output attitude information, but that exceeded estimated attitude degree storing errors of IRU by 1 degree, and STT measured attitude information (actual attitude) continued to reject. (fact)

*The time that Earth comse in sight of STT

No telemetry （estimated ; We cannot play back the data recorder for now.）

USC: JAXA Uchinoura station

5.1.3 FDIR of Sun Angle Anomaly (Continuation of the Attitude Anomaly) (1/2)

(1) Facts

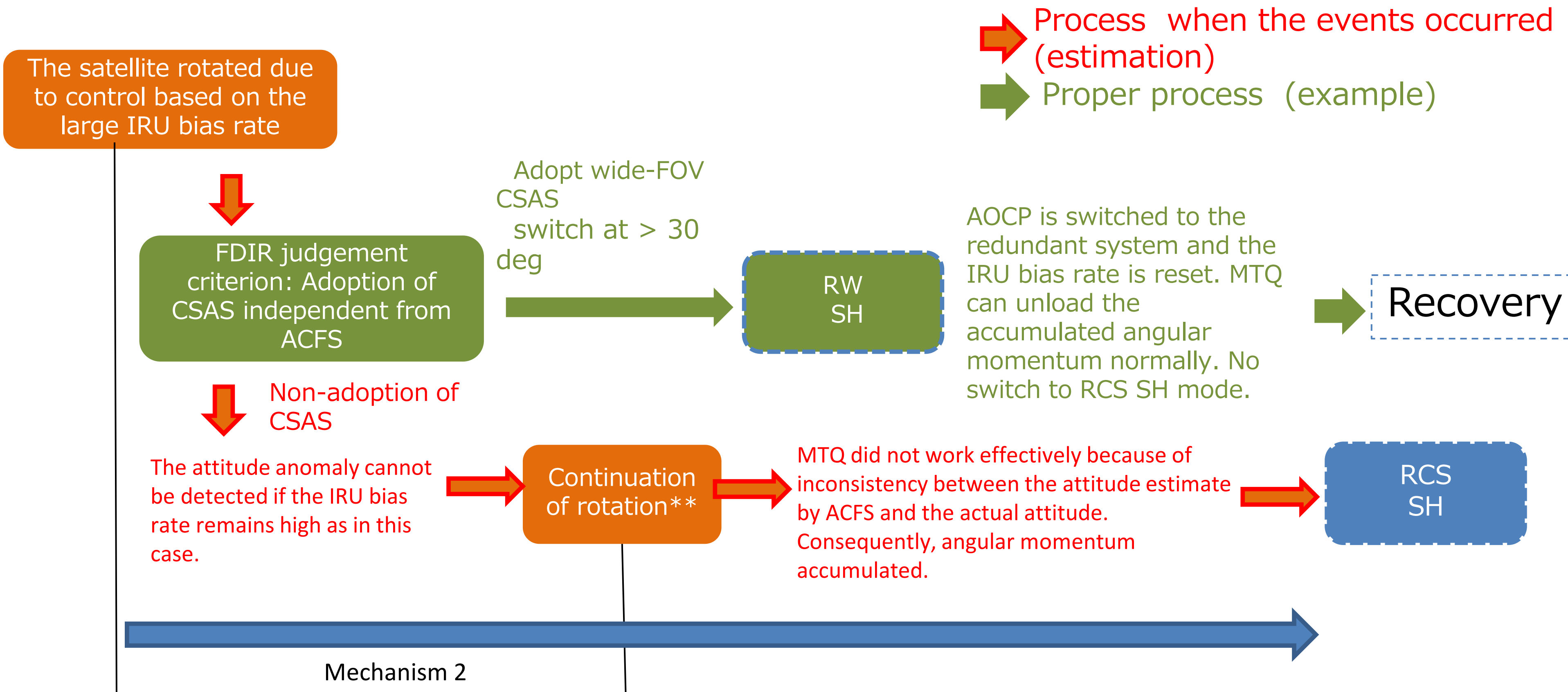
- After the attitude anomaly, the satellite started rotating at a rate of 21.7 deg/h and the SAPs were not pointed toward the sun. Although the attitude differed from the planned one, assessment of the attitude anomaly was not implemented. The satellite switched to SH mode during the MGN pass. This occurred from 09:52 to 10:04 on March 26.
- In the design phase, it was decided that estimates by ACFS, not CSAS, would be used in the judgement to switch to SH mode due to the sun angle. This was because the linear field of view (20 deg) of CSAS was narrower than the required normal attitude range (30 deg).
- In consideration of possible errors in the ACFS estimates, an automatic detection function using a non-updated flag of the STT was not adopted, nor was a system to switch to FDIR mode when the sun presence became larger than 41 deg. Instead, measures were implemented by operations.

5.1.3 FDIR of Sun Angle Anomaly (Continuation of Attitude Anomaly) (2/2)

(2) Direct factors (estimation)

- The attitude anomaly (the anomaly of the IRU bias rate) could not be detected because the satellite was designed to rely on only the ACFS estimates (not use CSAS) to detect an anomaly of the sun direction and switch to the SH attitude. Consequently, the attitude anomaly continued.
- Unloading by the MTQ failed due to the attitude anomaly. This led accumulation of RW angular momentum, which ultimately exceeded the upper limit (120 Nms). At this time, the satellite detected some anomaly of control by RW and switched to the RCS SH, in which thrusters were used for attitude control.

Mechanism 2: Continuation of the Attitude Anomaly　FDIR Design



Process　when the events occurred (estimation)

Proper process　(example)

The satellite rotated due to control based on the large IRU bias rate

FDIR judgement criterion: Adoption of CSAS independent from ACFS

Adopt wide-FOV CSAS switch at > 30 deg

RW SH

AOCP is switched to the redundant system and the IRU bias rate is reset. MTQ can unload the accumulated angular momentum normally. No switch to RCS SH mode.

Recovery

Non-adoption of CSAS

The attitude anomaly cannot be detected if the IRU bias rate remains high as in this case.

Continuation of rotation**

MTQ did not work effectively because of inconsistency between the attitude estimate by ACFS and the actual attitude. Consequently, angular momentum accumulated.

RCS SH

Mechanism 2

Sequence of events

Attitude anomaly
(at 04:10 [estimated from telemetry],　non-visible condition)

Continuation of attitude anomaly
MSP (05:49-06:02)
MSP (07:31-07:44)
MGN (09:52-10:04)

Note that the satellite was designed to switch to RCS SH just after switching to the RW SH if the judgment was based on the accumulated angular momentum.

**AOCS of ASTRO-H judges the attitude anomaly based on only the ACFS estimates, and does not use CSAS.

5.1.4 Inappropriate Parameter Setting (1/5)

(1) Facts

JAXA carries out the operation of ASTRO-H under a support contract with an operations support company.
ASTRO-H is a special satellite whose mass properties change after EOB extension. Accordingly, after EOB extension on orbit, parameters related to the mass properties (center of mass and moment of inertia [MOI]) have to be changed.

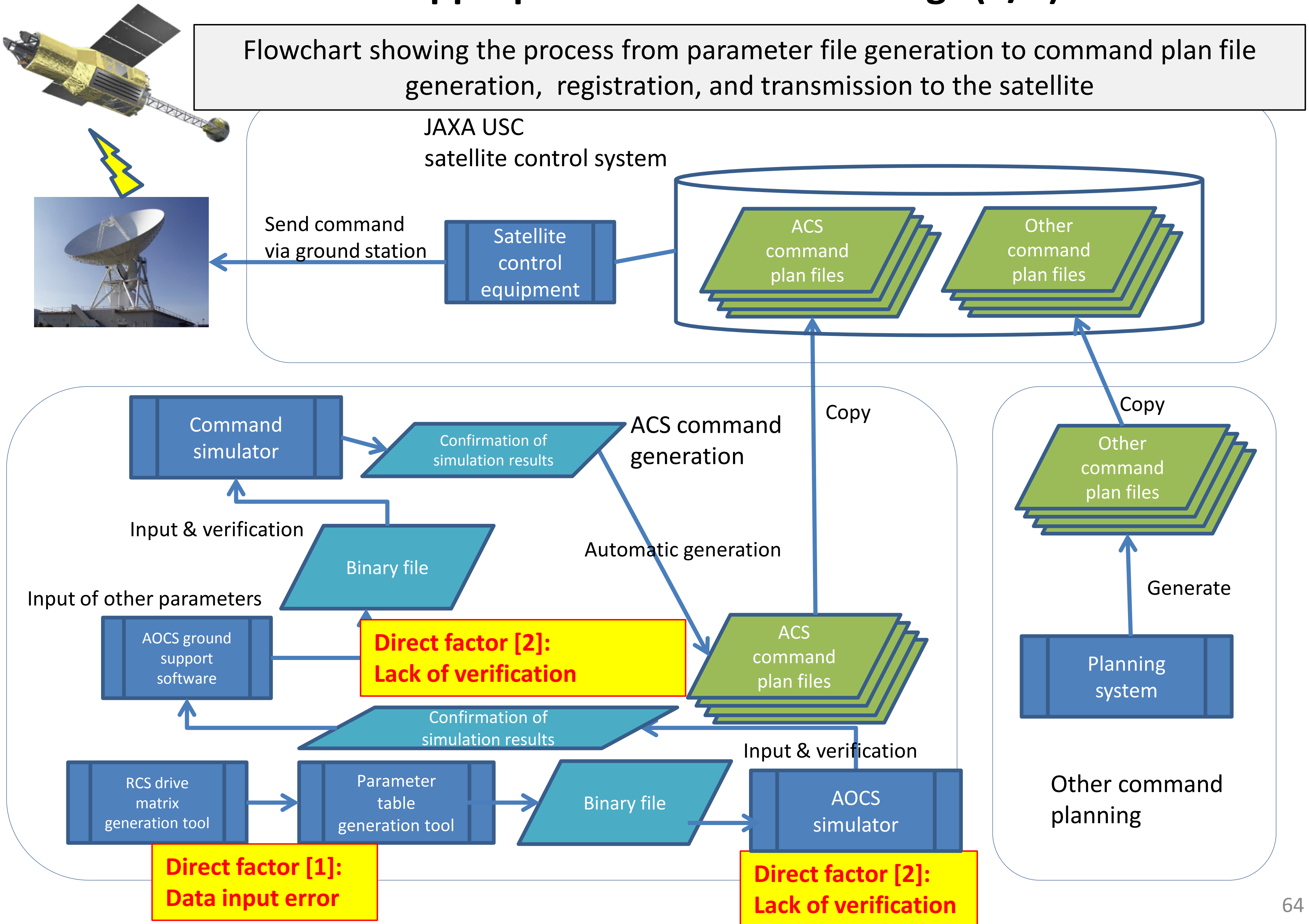
1. Feb 25: As a part of operations to change parameters after EOB extension, JAXA held discussions with the support company and decided to change the thruster control parameters according to the actual properties of the thrusters. The company started the process. Note that this operation (changing the parameters) was not described in the documents prepared prior to launch that regulated the operational plan. In addition, details of this operation (which parameters are changed and how) were not shared between the support company and JAXA.

5.1.4 Inappropriate Parameter Setting (2/5)

2. There were errors in data input by the support company when the updated thruster control parameters were calculated. Accordingly, inappropriate parameters were derived.
3. The support company was busy with duties on that day. One reason for this was that the company had to perform a task that was not described in the document governing the operational plan. This situation led to miscommunication of operational instructions between staff members of the company. Thus, a part of required verification was not implemented.
4. JAXA, which was in charge of operations, did not confirm the preparation process for changing the thruster control parameters. Then, JAXA, without noticing the omission of the verification, ordered the implementation of the operation.
5. Feb 28: After EOB extension, an operator followed the instruction given by JAXA, and sent the parameters prepared in item 2 above to the satellite.

5.1.4 Inappropriate Parameter Settings (3/5)

Flowchart showing the process from parameter file generation to command plan file generation, registration, and transmission to the satellite



JAXA USC
satellite control system

Send command
via ground station

Satellite control equipment

ACS command plan files

Other command plan files

Copy

Copy

Command simulator

Confirmation of simulation results

ACS command generation

Input & verification

Binary file

Automatic generation

Input of other parameters

AOCS ground support software

Direct factor [2]:
Lack of verification

ACS command plan files

Confirmation of simulation results

Input & verification

RCS drive matrix generation tool

Parameter table generation tool

Binary file

AOCS simulator

Direct factor [1]:
Data input error

Direct factor [2]:
Lack of verification

Other command plan files

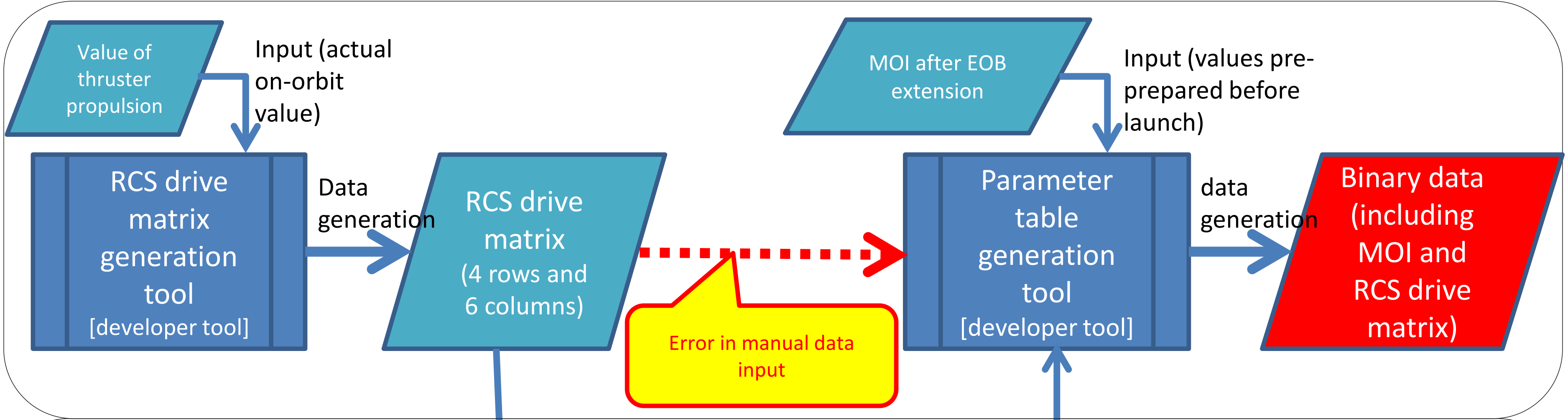
Generate

Planning system

Other command planning

5.1.4 Inappropriate Parameter Settings (4/5)

Flowchart showing the process for command file generation on Feb 25 (expanding the bottom left part of the flowchart on the previous page)



Value of thruster propulsion

Input (actual on-orbit value)

RCS drive matrix generation tool [developer tool]

Data generation

RCS drive matrix (4 rows and 6 columns)

Error in manual data input

MOI after EOB extension

Input (values pre-prepared before launch)

Parameter table generation tool [developer tool]

data generation

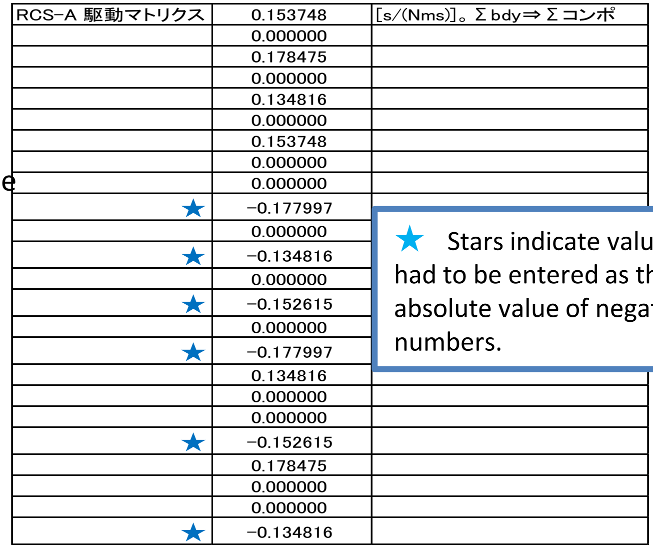
Binary data (including MOI and RCS drive matrix)

Output of the "RCS drive matrix generation tool"

$$\begin{pmatrix} 0.153748 & 0.000000 & 0.178475 & 0.000000 & 0.134816 & 0.000000 \\ 0.153748 & 0.000000 & 0.000000 & \mathbf{-0.177997} & 0.000000 & \mathbf{-0.134816} \\ 0.000000 & \mathbf{-0.152615} & 0.000000 & \mathbf{-0.177997} & 0.134816 & 0.000000 \\ 0.000000 & \boldsymbol{-0.152615} & 0.178475 & 0.000000 & 0.000000 & \mathbf{-0.134816} \end{pmatrix}$$

reference

Input to "Parameter table generation tool"



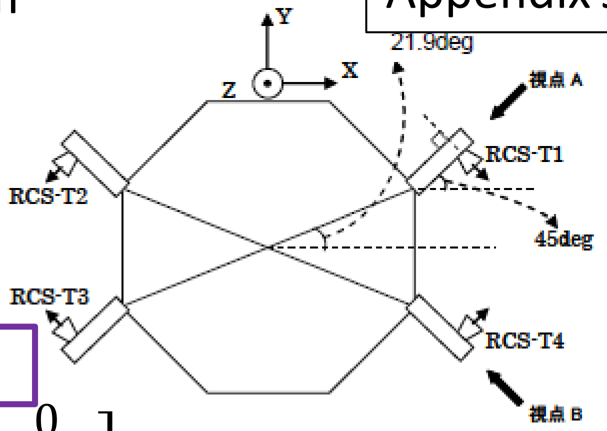
RCS−A 駆動マトリクス	0.153748	[s/(Nms)]。Σbdy⇒Σコンポ
	0.000000	
	0.178475	
	0.000000	
	0.134816	
	0.000000	
	0.153748	
	0.000000	
	0.000000	
★	−0.177997	
	0.000000	
★	−0.134816	
	0.000000	
★	−0.152615	
	0.000000	
★	−0.177997	
	0.134816	
	0.000000	
	0.000000	
★	−0.152615	
	0.178475	
	0.000000	
	0.000000	
★	−0.134816	

★ Stars indicate values that had to be entered as the absolute value of negative numbers.

An overview of satellite behavior resulting from the "inappropriate part of the RCS control parameter settings" is shown on the next page. (Appendix J)

Appendix J: Overview of satellite behavior resulting from the "inappropriate part of the RCS control parameter settings"

Appendix J



Below is an overview of the satellite's behavior when inappropriate parameters were set. All values should be positive for coefficients to determine thruster injection duration for a negative torque. However, some negative values were input in this case.

Ex.) If the -Z torque request value was set to 100 Nms

$$\begin{array}{l}\text{RCS-T1 injection time (s)}\\ \text{RCS-T2 injection time (s)}\\ \text{RCS-T3 injection time (s)}\\ \text{RCS-T4 injection time (s)}\end{array}\begin{bmatrix}0\\-100\\0\\-100\end{bmatrix}=\begin{bmatrix}1&0&1&0&1&0\\1&0&0&-1&0&-1\\0&-1&0&-1&1&0\\0&-1&1&0&0&-1\end{bmatrix}\begin{bmatrix}0\\0\\0\\0\\0\\100\end{bmatrix}\begin{array}{l}\text{+X torque product request (Nms)}\\ \text{-X torque product request (Nms)}\\ \text{+Y torque product request (Nms)}\\ \text{-Y torque product request (Nms)}\\ \text{+Z torque product request (Nms)}\\ \text{-Z torque product request (Nms)}\end{array}$$

Processing for saving fuel: Subtract the "minimum" injection time (s) of each RCS from the time each second

$$\begin{bmatrix}100\\0\\100\\0\end{bmatrix}$$

If each torque request value is 100, the following is obtained.

$$\begin{array}{cccccc}\begin{bmatrix}100\\100\\0\\0\end{bmatrix}&\begin{bmatrix}100\\100\\0\\0\end{bmatrix}&\begin{bmatrix}100\\0\\0\\100\end{bmatrix}&\begin{bmatrix}100\\0\\0\\100\end{bmatrix}&\begin{bmatrix}100\\0\\100\\0\end{bmatrix}&\begin{bmatrix}100\\0\\100\\0\end{bmatrix}\\ \text{+X}&\text{-X}&\text{+Y}&\text{-Y}&\text{+Z}&\text{-Z}\end{array}$$

The values shown on this page are simplified for explanation. The actual values are different

As a result, even if the torque request is set around the negative axis, the result becomes the positive direction for thruster injections and acceleration continues in one direction around all XYZ three axes.

5.1.4 Inappropriate Parameter Settings (5/5)

(2)Direct Factors:

[1] **Errors in data input during parameter calculation**

- When values are input into the "parameter table generation tool," negative values that were output from "RCS drive matrix generation tool“ must be converted to positive values. However, the operator from the support company omitted this procedure.
- The operator had experience using these tools but was doing this work for the first time, and therefore did not know about the need to convert from negative to positive.
- The two tools were not designated as “operational tools“ by JAXA. Instead, they were development tools for experts who were all familiar with the configuration, and these tools were constructed for development testing. No manual was prepared, and no operational training was carried out.

[2] Lack of verification of the data

- The support company did not use the simulator to verify the generated thruster control parameters.
- An operator in charge from the support company made an orally asked another operator to run the simulation, but failed to indicate the necessity of verification for the change in thruster control parameter. Verification of the results was not performed.
- JAXA did not do a final check of operational readiness regarding the change of thruster control parameters.
- Neither the support company nor JAXA did not define a process for confirming verification results in order to proceed further. The process to confirm the

5.2.1 Issues for Consideration in the Design Phase (1/6)

(1) Factual relations

- Design of the ASTRO-H ACS

  JAXA adopted a design inheriting technologies from “Suzaku” to the extent possible, thereafter proceeding with the conceptual design, and at the time of SDR in 2008, included items related to the attitude control design in the JAXA mission system requirement documents. After that, a system designer company performed design work after the basic design phase.

Fundamental concepts related to attitude system design

Because ASTRO-H required high observational capabilities and a large fuselage, the following approaches were adopted:

- ➢ High-precision, highly stable orientation determination despite increased heat deformation and perturbation due to increased size.
- ➢ To cope with increased gravity gradient torque from the larger fuselage, RW with large angular momentum and MTQ capable of generating a large disturbance removal torque.
- ➢ Adoption of a zero-momentum system, not a bias-momentum system with bias angle momentum like the one in Suzaku.

Fundamental concepts related to FDIR design

To avoid reduced observation time due to transition to SH mode, operations during normal control must retain redundancy for automatic fail tolerance or fail operations, without unnecessary transitions to fail-safe mode.

5.2.1 Issues for Consideration in the Design Phase (2/6)

- Design review and review meetings

  System engineers proceeded with system design as specified on the previous page.
  The JAXA project received support from each operator as a result of system design, and the following design review committees were formed with members from inside and outside of JAXA.

  - JAXA-hosted technical review committees
    - Apr 2008 : System Definition Review (SDR)
    - May 2010 : Preliminary Design Review (PDR)
    - Nov 2011 : Control Design Review, Pt. 1 (CDR1)
    - Feb 2012 : Detailed Design Review, Pt. 1 (CDR1) [Note 1]
    - Jun 2012 : Control Design Review, Pt. 2 (CDR2)
    - Nov 2014 : Detailed Design Review, Pt. 2 (CDR2) [Note 2]

  Note 1: System CDR1 covered all EM/FM subsystems and satellite systems, with the exception of the SXS
  Note 2: System CDR2 covered the SXS FM reflecting EM verification results, all corrections to designs after CDR1, and the implementation of the corrections in the satellite bus system.

  Users and others attended design meetings in the JAXA project to receive reports from manufacturers and to verify the progress status.

  - From 2008 to 2015, there were 21 meetings to discuss the design between JAXA, businesses, universities, and other stakeholders.

5.2.1 Issues for Consideration in the Design Phase (3/6)

(2) Specific issues

■ Anomaly mechanism 1 (STT, AOCS design)

STT behavior

- In design and verification for standalone STT development, the logic for calculations of acquisition mode attitude rate, and the parameter values for star usage conditions, were designed with an emphasis on acquisition speed and precision, which resulted in insufficient robustness reflecting actual usage conditions. There was also insufficient verification planning.

AOCS design

- In design of an attitude determination system that met with demands for securing user observation time, overall verification by JAXA and supporting organizations was insufficient to ensure a system for satellite safety.
- There was debate on both sides regarding readjustment of design parameters for the CDR2 attitude system and Kalman filter. JAXA-sponsored subcommittee meetings confirmed that estimated values of the Kalman filter bias rate increased, and in later discussions decided that readjustment was unnecessary, but not all committee members shared this conclusion.
- An automatic detection function using the STT non-update flag was also discussed as part of the FDIR, but JAXA and supporting companies determined that this could be accommodated through ground support, so this was not implemented.

5.2.1 Issues for Consideration in the Design Phase (4/6)

- Anomaly mechanism 2 (FDIR behavior)
  - Regarding the Coarse Sun Aspect Sensor (CSAS) not being used in the determination of the transition to SH mode, the linear region of the field of view of CSAS (20deg.) was narrower than the observational field of view (30deg.), so the solar direction could not be fully contained, leading to the possibility of an unnecessary transition to SH mode. Because of this, it was decided to use values calculated from ACFS in place of CSAS at the request of users prioritizing observation continuity.
  - In consideration of ACFS calculation error, automatic detection using the STT non-update flag and the logic for switch to FDIR when sun presence was outside the 41 deg. field of view were not used. Instead, this was addressed through operation using telemetry output of continuous non-update count, but corresponding specific operations were insufficiently communicated.

5.2.1 Issues for Consideration in the Design Phase (5/6)

- Anomaly mechanism 3 (parameter settings)
  - As a part of worst-case scenario analysis during parameter settings, there was a confirmation of attitude control performance before and up to EOB extension, in which mass characteristics and thruster control parameter validity were investigated by simulation. However, parameters for immediately after EOB extension were calculated from the actual tank pressure, and therefore were not prepared beforehand. A topic for consideration is the necessity of preparing and setting in advance parameters used in initial operation, preparing parameters for minimal initial burden through only differential information, and implementing other such measures.

- Anomaly mechanism 4 (breakage and separation)
  - Structural satellite design including SAPs and EOB was conducted according to ratings based on the highest load conditions by part expected to be encountered during construction, during assembly, during launch, and on orbit. This is the general approach taken in spacecraft design, both in Japan and overseas. No abnormalities were observed in relation to structural natural frequency from launch to SAP deployment and EOB extension, so it is considered that such a structural strength design is not problematic.

5.2.1 Issues for Consideration in the Design Phase (6/6)

(3) Summary of design phase issues

- The descriptions of requests for mission system requirements in the ACS design are imbalanced. While there there are detailed requirements for the retention of good observational conditions, there are few requirements for safety and reliability, and as a result there is imbalance in system safety both at JAXA and at its supporting organizations.
- In ACS design, there were insufficient items for design consideration to avoid burdens during initial operational phases after launch, such as whether parameter settings should be prepared beforehand and switched, or whether only differentials should be altered.
- There was no comprehensive management of concerns in design review committees, etc. Methods for committee verification from projects and third parties were insufficiently effective.

5.2.2 Issues for Consideration in the Manufacturing and Testing Phases (1/2)

(1) Factual relations

Following receipt of CDR results, the following schedule for attitude system flight equipment and testing was adopted:

(1) Aug – Dec 2013: AOCP interlocking test
(2) Jan – Jun 2014: Satellite primary interlocking test (with AOCS)
(3) Dec 2014 – Feb 2015: Attitude system comprehensive testing
(4) Mar – Oct 2015: Satellite comprehensive testing (with AOCS)

5.2.2 Issues for Consideration in the Manufacturing and Testing Phases (2/2)

(2) Specific issues

- Anomaly mechanisms 1–3 (STT behavior, AOCS design, FDIR behavior, parameter settings)
  While there were some schedule delays during the development period due to equipment problems, these problems were addressed and comprehensive testing of the attitude system was completed in Feb 2015. The final results of the comprehensive testing verified that there were no problems.

- Anomaly mechanism 4 (breakage and separation)
  Evaluation based on inspection records at the time of manufacture indicated no problematic items related to the SAP attachment parts or EOB that presumably broke off and separated as a result of large loads during rotation. This issue was likely not related to manufacturing or testing issues.

(3) Summary of manufacturing and testing phases

- While there were schedule delays during development of control system equipment, it was confirmed that all appropriate actions were taken and the launch finally occurred. Current issues are therefore not problems related to manufacturing and testing.
- Issues related to SAP attachments and EOB are also not related to manufacturing and testing.

5.2.3 Issues for Consideration in the Operational Phase (1/4)

(1) Factual relations

- ASTRO-H operational planning
  - Satellite operation is primarily conducted by JAXA. Operational planning for critical phases is proposed by operational support organizations in consultation with JAXA, manufacturers, and the support organizations and is approved by JAXA.
  - During the pre-launch period from Aug 2015 through Feb 2016, approximately 20 operational coordination committee meetings were conducted (over 60 meetings if coordination committee meetings by subsystem are included). Based on these meetings, planning, procedural, and operational planning standards for critical phases were established.
    However, there was no discussion of operations for changing parameters in consideration of changes in mass characteristics immediately after EOB extension, so no related operational documents were created.

5.2.3 Issues for Consideration in the Operational Phase (2/4)

(2) Specific issues

- Anomaly mechanism 1 (STT behavior, AOCS design)
  - After launch, there were multiple unknown events related to STT (events where tracking mode switched to acquisition mode, or where an abnormally long time was taken to transition to tracking mode), but these issues remained unresolved, with STT placed in standby mode as during occultation of tracked stars by Earth, and initial confirmation operations and test observations were continued. (STT parameter tuning remained incomplete.)
  - There were no substantive reports of these unknown, on-orbit STT events from the satellite control team to the S&MA members within ISAS.

- Anomaly mechanism 2 (FDIR behavior)
  - As described in Section 5.2.1, “this was addressed through operation using telemetry output of continuous non-update count, but corresponding specific operations were insufficiently communicated,” and as a result there was no response from the ground.
  - Attitude change maneuvers were completed at the very end of visibility and followed by only ranging operations at overseas stations, so verification of the satellite status at times of visibility was not performed.
    - Details in Reference (4): “Command operations, ranging operations at overseas stations, and visibility of attitude change maneuvers for USC visible group.”
  - Operational control conditions were incompletely organized before launch, and maneuvers were performed while on-orbit issues remained unresolved.

5.2.3 Issues for Consideration in the Operational Phase (3/4)

- Anomaly mechanism 3 (parameter settings)
  - Direct factors were "data input errors during parameter creation" and "incomplete verifications." It is difficult to reduce human error to zero, so satellite operational systems (including operational procedures, etc.) are generally constructed in consideration of potential errors.
  - Therefore, measures (designs, etc.) should be considered that address problematic mechanisms (work flow, systems) that allowed such human error and missed verifications in operations.

The following was also found:

- Training and rehearsals were conducted for only the initial day of critical phases and normal operations. No rehearsals were performed for parameter setting changes.
- Operational procedure plans were updated daily, congesting the workload of operational support organizations involved with the ACS.
- All tools for parameter setting were positioned as tools for use by experienced developers during development and testing, so no manuals were prepared and no operational training was conducted. There was also no overall manual of procedures for the parameter setting and simulation process.
- In the end, JAXA did not verify the operational preparation status of parameter changes for thruster control.

- Anomaly mechanism 4 (breakage and separation)
  - This event was the result of load application in excess of structural design ratings. Although operational problems led to the excess load, mechanical failure under such loads is not an issue particular to operations.

5.2.3 Issues for Consideration in the Operational Phase (4/4)

(3) Summary of operational phase issues

- Risks in the initial phase of satellite operation were underestimated, leading to imbalances in overall system safety.
  - Operations left the satellite in an unobservable position without verification after maneuvers were performed at the initial functional confirmation phase under unstable conditions. While it was the operational policy of USC to view this as a transition to normal operations, such operations were premature.
  - There were poorly defined evaluation criteria for performing maneuvers at non-visible times.
  - There was insufficient consideration of operational risks resulting from additional parameter setting and verification operations during critical phases, which are the time at which operations are already most congested.

- There was an underestimation of the importance of operational plans, operational manuals, personnel training, etc., and insufficient preparation of planning documents, manuals, and operational training.
  - In the maintenance of procedural manuals, there was no overall requirement for the preparation of manuals for all procedures, tools, and verification of operation results.
  - On-ground delays in launch preparation were the result of insufficient time allotment between resolution of committee actions and the start of actual implementation.
  - Operational training focused on only launch day, the first day of critical phases, and normal operations, so there was insufficient consideration of a wide range of topics.

６. MEASURES AND REFORMS

（To be proposed in the next committee meeting）

7．SUMMARY

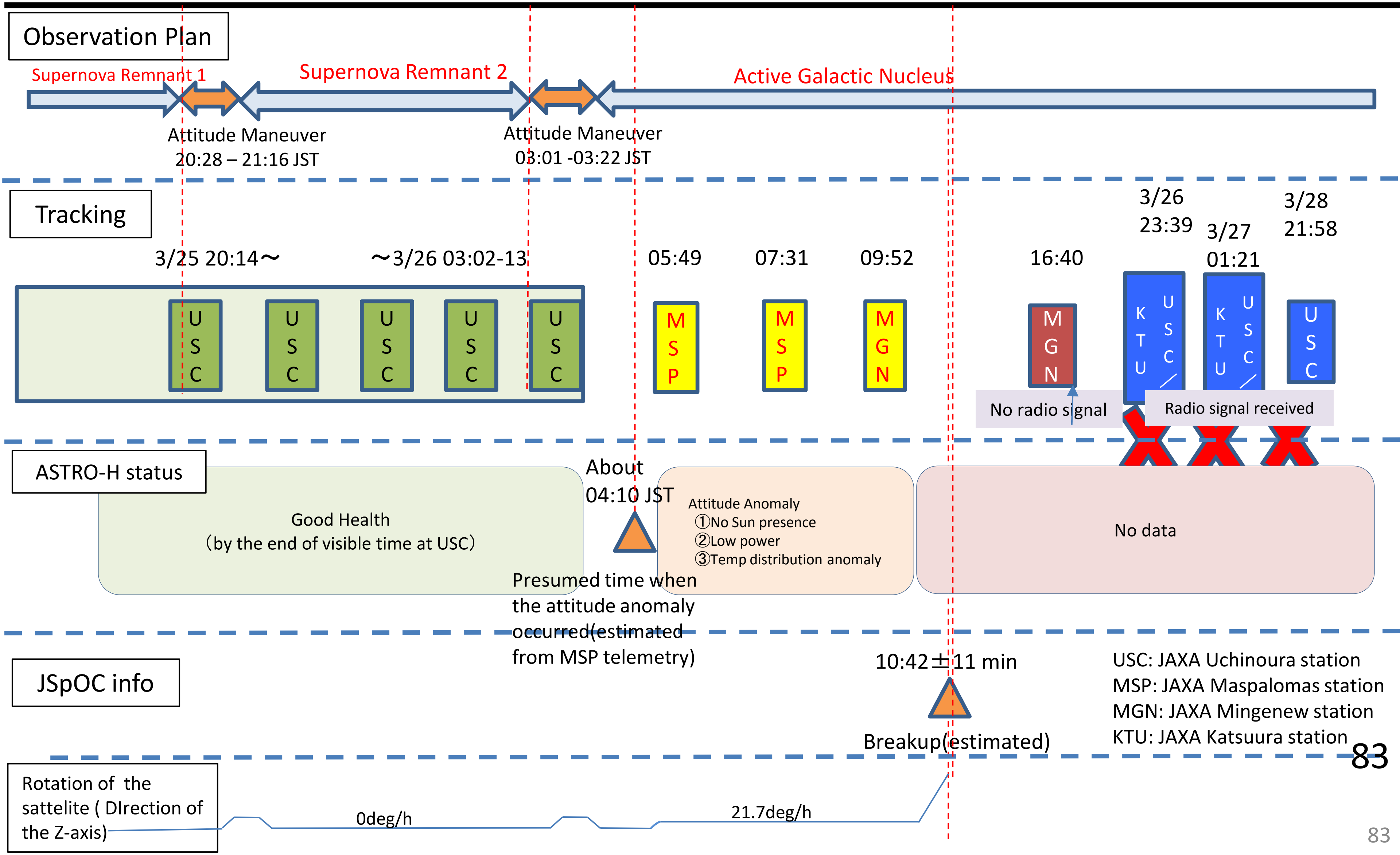
（To be proposed in the next committee meeting）

REFERENCES

Reference: Hitomi Sequence of Events

Reference

The chart below shows a time sequence for the initial phase of satellite operation, satellite tracking, satellite condition on each events, and JSpOC information.



Observation Plan

Supernova Remnant 1

Supernova Remnant 2

Active Galactic Nucleus

Attitude Maneuver
20:28 – 21:16 JST

Attitude Maneuver
03:01 -03:22 JST

Tracking

3/25 20:14〜

〜3/26 03:02-13

05:49

07:31

09:52

16:40

3/26
23:39

3/27
01:21

3/28
21:58

USC USC USC USC USC MSP MSP MGN MGN KTU USC/ KTU USC/ USC

No radio signal

Radio signal received

ASTRO-H status

Good Health
（by the end of visible time at USC）

About
04:10 JST

Presumed time when the attitude anomaly occurred(estimated from MSP telemetry)

Attitude Anomaly
①No Sun presence
②Low power
③Temp distribution anomaly

No data

JSpOC info

10:42±11 min

Breakup(estimated)

USC: JAXA Uchinoura station
MSP: JAXA Maspalomas station
MGN: JAXA Mingew station
KTU: JAXA Katsuura station

Rotation of the sattelite (DIrection of the Z-axis)

0deg/h

21.7deg/h

Behaviors of STT

Reference

(1)Facts（continue)

⑦　Summary of the Event A ～ D

(∗1) Angle between the centers of the earth and the field of view (FOV)

(∗2) Day or Night of the earth surface to the direction of the FOV

(∗3) Earth presence in the FOV

Event	No.	Tracking → Acquisition Time & Date	Occurrence	Behavior	Sunshine/shade	Angle (*1)(deg)	(*2)	The earth presence (*3)	SAA	Cause
B	1	2/28 5:37:56	1	(a)	sunshine	47.5	Daytime			Cause 2
	2	2/28 10:22:26	1	(a)	sunshine	32.0	Daytime			
	3	2/29 2:18:39～ 2:18:47	3	(b)	sunshine	19.2	Daytime	yes		Cause 1
	4	3/3 0:44:41	1	(b)	sunshine	19.8	Daytime	yes		
	5	3/7 20:06:57～ 20:07:05	2	(c)	sunshine	5.9	Daytime	Yes		
	6	3/7 20:31:52	1	(b)	sunshine	6.2	Night	yes	SAA	
	7	3/8 0:40:05	1	(b)	sunshine	-16.0	Daytime	yes		
	8	3/15 23:26:01～ 23:26:05	**2**	(c)	sunshine	21.4	Daytime	yes		
	9	3/15 23:33:56～ 23:34:05	3	(b)	sunshine	26.2	Daytime	yes		
	10	3/16 14:49:03～ 14:49:09	2	(c)	shade	2.4	Night	yes		
	11	3/16 15:13:35	1	(a)	sunshine	17.8	Daytime	yes		
	12	3/16 17:01:00	1	(c)	sunshine	16.0	Daytime	yes	SAA	
	13	3/16 17:40:50 ～ 17:41:40	8	(b)	shade	1.2～4.8	Night	yes		
	14	3/16 18:37:07～ 18:37:12	2	(c)	sunshine	16.2	Daytime	yes		
	15	3/16 19:16:33～ 19:16:39	2	(b)	shade	1.0	Night	yes		
A	16	3/25 19:10:00	?	(a)	sunshine	33.1	Night		After passing SAA	Cause 2
C	17	2/27 15:07:34	1	(a)	sunshine	32.6	Daytime			Cause 2
	18	3/15 20:15:06～20;15:11	2	(c)	sunshine	16.5	Daytime	yes		Cause 1
	19	3/19 21:35:27	1	(a)	sunshine	96.3	Daytime			Cause 2
D	20	2/19 11:16	1	(d)	sunshine	0	Daytime	yes		Cause 1

(a): Not enough star,　(b): end of the earth presence in FOV,

(c) :beginning of the earth presence in FOV, (d): the earth covers FOV totally

Reference: the way of judgment to start the maneuver at the end of the real time operation pass (1/2)

1. Preconditions

- ASTRO-H has to change its attitude frequently to observe various objects. In some cases, the satellite has to change its attitude several times per day to meet observational requirement. However, USC, the main control station of ASTRO-H, can communicate with the satellite only 5 times per day. Therefore, it is inevitable to carry out "maneuver in USC invisible situations, that is, the completion maneuver can not be confirmed by telemetry in real-time" (hereafter "the Maneuver A").

2. Plan and the status of implementation of the AOCS

- JAXA prescribed the plan of AOCS check-out in prior the launch as a part of the initial operation protocol. After the critical phase, this part was included in a part of the plan of the performance verification phase, and JAXA managed the plan and the records integrally under support by the supporting agent. However, the plan of the performance verification phase was not the official document of JAXA in charge of the operation.
- In the list of the AOCS check-out plan, some items were set deadlines like before the end of critical phase or in prior the normal operation, and others were not set deadlines.
- The records shows all the items that had to be completed within the critical phase were actually completed before the deadline. When these events occurred, there were items of incompletion among the items those had to be completed in prior the normal operation. Specially, the STT check-out was not completed (the timing of implementation was also unfixed.) and in the phase of inspection on the events happened on orbit.
- The AOCS check-out plan did not prescribe the condition to carry out the Maneuver A. JAXA determined that the implementation was judged on the basis of the satellite status during actual operation.

Reference: the way of judgment to start the maneuver at the end of the real time operation pass (2/2)

3. Actual Operation

① Command operation at USC & ranging operation at overseas stations

- Till the end of the critical phase (Feb. 28th), passes as many as possible were assigned and carried out 24-hour command operation and monitoring of the satellite status.
- After the critical phase (from Feb. 29th to Mar. 16th), command operation was carried out only at USC, and MSP and MGN was used for ranging and monitoring.
- On Mar. 16th, the GPSR navigation solution was verified. Accordingly, since Mar. 17th, the orbit was determined by GPSR data instead of ranging. From the perspective of continuous verification of GPSR, JAXA determined to continue ranging operation without telemetry monitoring.

② Determination of the timing of attitude control maneuver

- Operations were proceeded by the following steps. First, maneuver was implemented to complete within visible time. And then, operation proceeded further: “start maneuver in visible condition and complete in the next visible”, “implement by time-line command during visible”, “implement by time-line command during invisible”, and “implement under the condition of operators on call”.
- The steps above were completed without a problem. Although the STT check-out was not completed, the completion of the IRU check-out was confirmed. Accordingly, the operation was carried out: the maneuver started from the end of USC visible time, and the satellite was operated under invisible condition for a long time without monitoring telemetry in the next visible chance.

■ As described ①&②, JAXA proceeded the mission step-by-step to prepare for the normal operation phase while watching the status of the initial function verification.

Reference: Heritage Information Table on Components, Software, Algorithm for Anomaly Mechanism①

Attitude Control System	Abb	Achievments results	TRL	Notes
Reaction Wheel	RW	Type-L HSRW	9	RW (Type-L wheel) developed as one of JAXA' s strategic components. Its rotator becomes larger than the same model (Type-M wheel) verified on orbit, and the maximum accumulated angular momentum was increased from 30 [Nms] to 80 [Nms]. QT test was implemented for an engineering model of Type-L qualified by JAXA.
Magnetic Torquer	MTQ	MTQ, newly developed by ZARM	6	Because of newly developed components, some tests and verification were performed by EM. (One for EM/ Three for FM3)
Star Tracker	STT	The next-generation STT (JAXA strategic components)	6	Sensor developed as one of the JAXA' s strategic components. QM was made as a qualified model and QT test was implemented.
Inertial Reference Unit	IRU	Used by GCOM-W、GCOM-C、ALOS-2, etc.	9	The IRU onboard ASTRO-H (Type-3AS) was installed 3 TDG spinning tops. One of 4 TDG spinning tops was replaced by a dummy in Type-3AS. Type-3A was frequently used (for example GCOM-W1 and ALOS-2) and verified on orbit. Type-3AS was installed on ASNARO and SPRINT-A (Hisaki).
Coarse Sun Aspect Sensor	CSAS	Used by many missions by developed ADCOLE	9	Solar sensor that was verified on orbit. SPRINT-A, ASNARO, Akatsuki, and so on use this sensor.
Geo Sensor	GAS	Developed by XARM Used by SPRINT-A	9	Magnetic sensor that was a component by the overseas project, and was made by replacing consumer parts to parts for a spacecraft. An EM was verified because this sensor was new one as for spacecraft.
3N Reaction Control System	RCS	Used by Halca, Suzaku, Akari, Akatsuki, etc.	9	Because the catalysis was changed, the lifetime test was implemented by using a model for the lifetime test.
Attitude Control Flight Software	ACFS	—	—	Followed the configuration of previous scientific satellites such as "Suzaku". In addition, by adoption of Space Wire, the standard middle ware, simulators and tools for component tests were standardized to reduce the cost and time.

ABBREVIATIONS

ACFS	**Attitude Control Flight Software**
AOCP	Attitude and Orbit Control Processor
AOCS	Attitude and Orbit Control Subsystem
ASTRO-H	X-ray satellite “Hitomi”
CAMS	Canadian ASTRO-H Metrology System
CDR	Critical Design Review
CdTe	Cadmium telluride
CSA	Canadian Space Agency
CSAS	Coarse Sun Aspect Sensor
EM	Engineering Model
EOB	Extensible Optical Bench
EOL	end of life
ESA	European Space Agency
FOB	Fixed optical bench
FDIR	Fault Detection Isolation and Reconfiguration
FM	Flight Model
FTA	Fault Tree Analysis
GPSR	GPS receiver
HXI	Hard X-ray Imager
HXT	Hard X-ray Telescope
IRU	Inertial Reference Unit
ISAS	Institute of Space and Astronautical Science
JAXA	Japan Aerospace Exploration Agency
JSpOC	Joint Space Operations Center
JST	Japan Standard Time
KTU	Katsuura Tracking and Communications Station
MELCO	Mitsubishi Electric Corporation
MGN	Mingenew ground station
MHI	Mitsubishi Heavy Industries、 Ltd.
MOI	moment of inertia

MSP	**Maspalomas ground station**
MTQ	Magnetic Torquer
NASA	National Aeronautics and Space Administration
NEC	NEC Corporation
NIPPI	NIPPI Corporation
PDR	Preliminary Design Review
PI	Principal investigator
RCS	Reaction Control Subsystem
RFP	Request for Proposal
RW	Reaction Wheel
SAA	South Atlantic Anomaly
SAC	Space Activities Commission
SANT	S-band Antenna
SAP	Solar Array Paddle
SDR	System Definition Review
SED	Space Engineering Development Co.、 Ltd.
SGD	Soft Gamma-Ray Detector
SH	Safe Hold
SHI	Sumitomo Heavy Industries、 Ltd.
SHNT	Shunt Dissipater
SRON	Netherlands Institute for Space Research
STT	Star Tracker
SXI	Sofr X-ray Imager
SXS	Soft X-ray Spectrometer
SXS-ADR	SXS Adiabatic Demagnetization Refrigerator
SXS-PSP	SXS Pulse Shape Processor
SXT-I	Soft X-ray Telescope for Imager
SXT-S	Soft X-ray Telescope for Spectrometer
S&MA	Safety and Mission Assurance
USC	Uchinoura Space Center
UT	Universal Time